UNIVERSITY OF BELGRADE
Faculty of Mechanical Engineering

10th International Scientific Conference

IRMES 2022

Research and Development of Mechanical Elements and Systems

PROCEEDINGS

"Machine design in the context of Industry 4.0 – Intelligent products"

Association for Design, Elements and Constructions

26 May 2022, Faculty of Mechanical Engineering, Belgrade, Serbia

10th International Scientific Conference - IRMES 2022

Research and Development of Mechanical Elements and Systems

PROCEEDINGS

Machine design in the context of Industry I4.0 – Intelligent products

Editors

Prof. Dr. Tatjana Lazović
Doc. Dr. Žarko Mišković
Prof. Dr. Radivoje Mitrović

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Dear Ladies and Gentlemen, Colleagues, Participants and Friends of IRMES 2022

The International Conference on Research and Development of Mechanical Elements and Systems – IRMES is organized under the auspices of the Association for Design, Elements and Constructions (ADEKO). The Conference has a long tradition of gathering scientists, researchers, academics, engineers and industry representatives, intending to exchange and share knowledge, ideas, experiences, innovations and research results in the field of engineering design, machine elements and systems.

So far, there have been nine editions, organized by several universities – members of the ADEKO association:

1995 – University of Niš, Faculty of Mechanical Engineering
1998 – University of Belgrade, Faculty of Mechanical Engineering
2000 – University of Podgorica, Faculty of Mechanical Engineering
2022 – University of East Sarajevo, Faculty of Mechanical Engineering
2004 – University of Kragujevac, Faculty of Mechanical Engineering
2006 – University of Banja Luka, Faculty of Mechanical Engineering
2011 – University of Niš, Faculty of Mechanical Engineering
2017 – University of Montenegro, Faculty of Mechanical Engineering
2019 – University of Kragujevac, Faculty of Engineering

More than a thousand authors participated in previous IRMES conferences, with more than a thousand papers published in total. The current IRMES conference was supposed to be held in 2021. However, due to the COVID-19 epidemic, it was postponed to 2022.

The main topic of the IRMES 2022 conference is „Machine design in the context of Industry 4.0 – Intelligent products". For sociologists and philosophers of science, the question remains whether the concept today, most commonly called Industry 4.0, is the true fourth technological revolution or the development/continuation of the third technological revolution – through further application of computers in production and logistics. It is indisputable that the essential question of this concept is the following: how do we introduce intelligent production in the industry? This consequently opens up new questions in the field of engineering design, theory and practice of technical systems and machine elements, and innovative product development – in the environment of the now global comprehensive Industry 4.0 concept or the Japanese answer to this concept – Society 5.0.

Teaching subjects and modules, such as Mechanical Elements, Machine Design, Innovative Product Development and others, has been the basis and generator of previous technological revolutions. Therefore, the question arises as to how to develop and improve the existing content of these subjects, but, also, what the best way for knowledge transfer is to keep the listed subjects as a driving force behind further development and improvement of philosophy and concept of Industry 4.0 (ie. how to implement new teaching methods, lessons, exercises, student projects, laboratory work, evaluation).

Taking into account the previously described facts, it is clear why an exchange of opinions, experiences and results between experts in the Industry 4.0 area is essential for social and industrial development. One of the best ways to do that is via public debate at international conferences, such as IRMES 2022, which we are very glad and proud to host and organize this year.

Belgrade, 26 May 2022

Prof. Dr. Radivoje Mitrović

University of Belgrade
Faculty of Mechanical Engineering
Department of General Machine Design

President of the IRMES 2022 Scientific Committee

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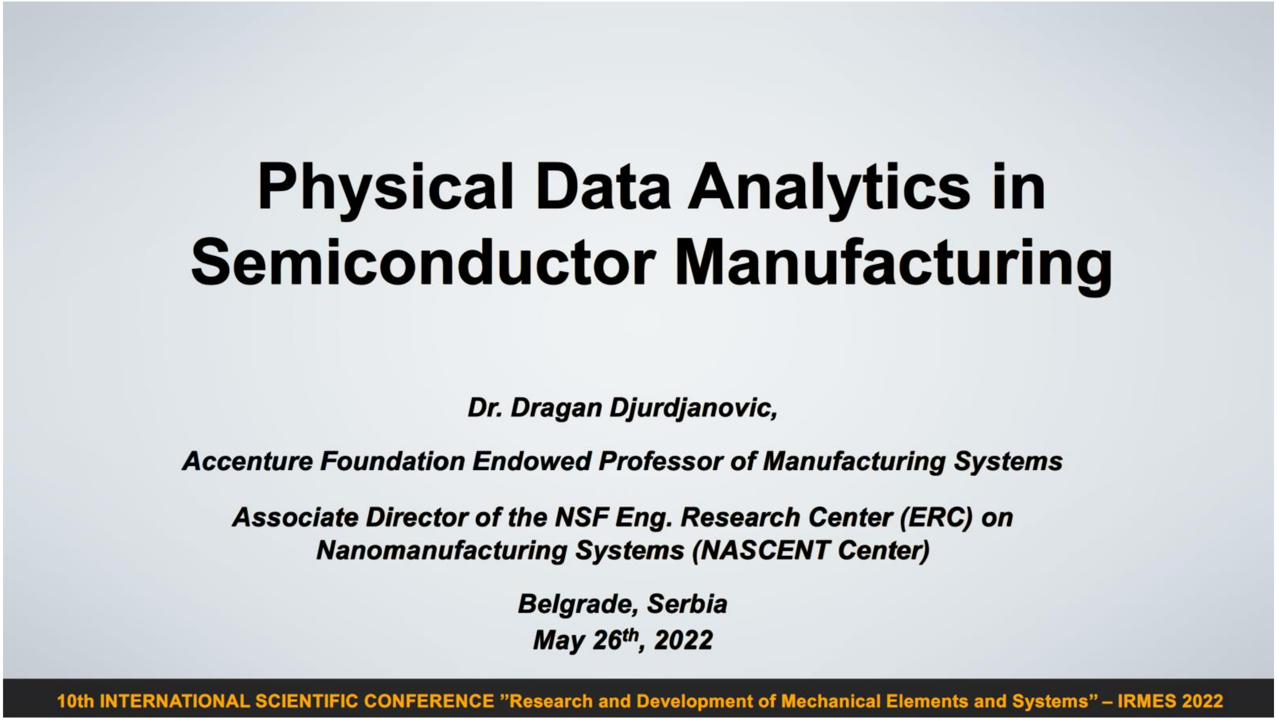
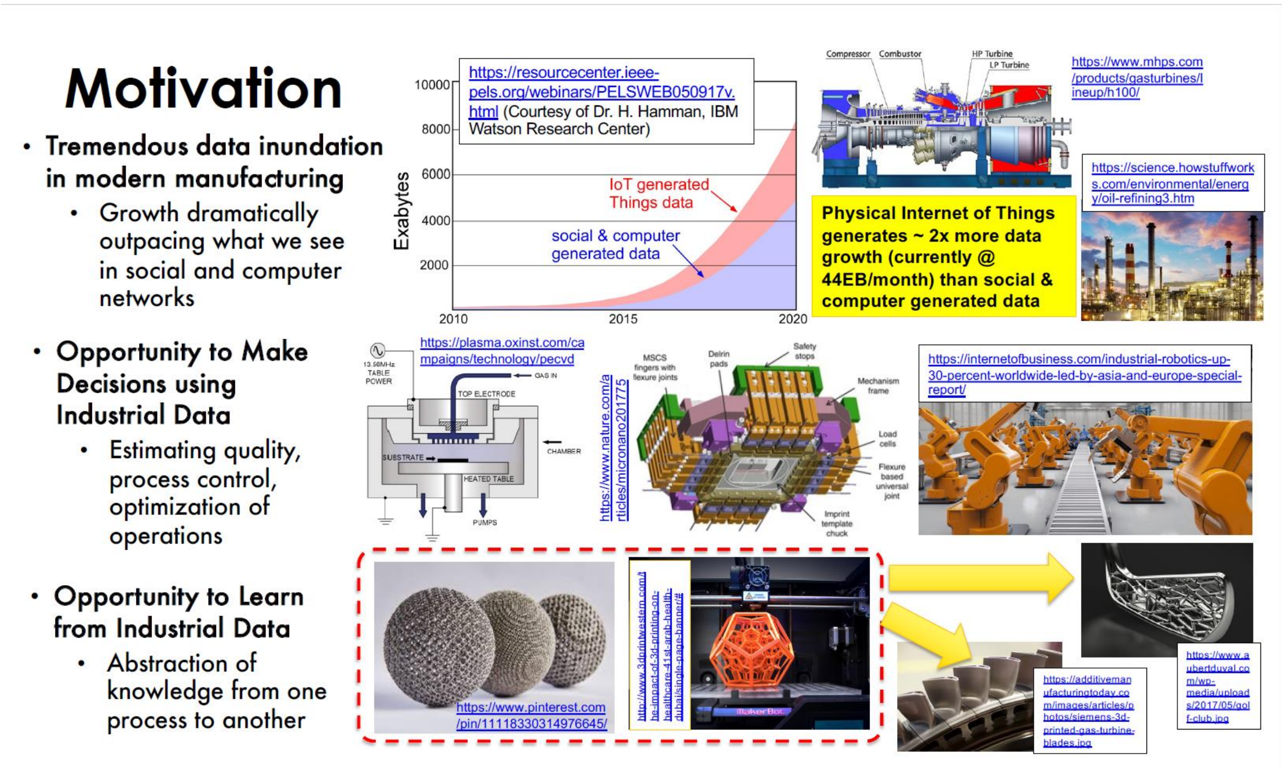
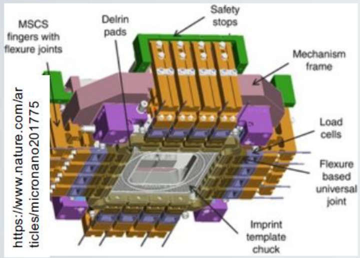
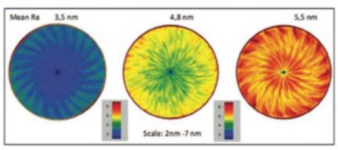
PLENARY LECTURES


Physical Data Analytics in Semiconductor Manufacturing
Dr. Dragan Djurdjanovic,
Accenture Foundation Endowed Professor of Manufacturing Systems
Associate Director of the NSF Eng. Research Center (ERC) on Nanomanufacturing Systems (NASCENT Center)
Belgrade, Serbia
May 26th, 2022
10th INTERNATIONAL SCIENTIFIC CONFERENCE "Research and Development of Mechanical Elements and Systems" – IRMES 2022


Motivation
• Tremendous data inundation in modern manufacturing
• Growth dramatically outpacing what we see in social and computer networks
• Opportunity to Make Decisions using Industrial Data
• Estimating quality, process control, optimization of operations
• Opportunity to Learn from Industrial Data
• Abstraction of knowledge from one process to another
https://resourcecenter.ieee-pels.org/webinars/PELSWEB050917v.html (Courtesy of Dr. H. Hamman, IBM Watson Research Center)
Exabytes
10000
8000
6000
4000
2000
2010
2015
2020
IoT generated Things data
social & computer generated data
Compressor
Combustor
HP Turbine
LP Turbine
https://www.mhps.com/products/gasturbines/lineup/h100/
https://science.howstuffworks.com/environmental/energy/oil-refining3.htm
Physical Internet of Things generates ~ 2x more data growth (currently @ 44EB/month) than social & computer generated data
https://plasma.oxinst.com/campaigns/technology/pecvd
13.56MHz TABLE POWER
GAS IN
TOP ELECTRODE
SUBSTRATE
CHAMBER
HEATED TABLE
PUMPS
https://www.nature.com/articles/micronano201775
MSCS fingers with flexure joints
Delrin pads
Safety stops
Mechanism frame
Load cells
Flexure based universal joint
Imprint template chuck
https://internetofbusiness.com/industrial-robotics-up-30-percent-worldwide-led-by-asia-and-europe-special-report/
https://www.pinterest.com/pin/11118330314976645/
https://additivemanufacturingtoday.com/images/articles/photos/siemens-3d-printed-gas-turbine-blades.jpg
https://www.aubertduval.com/wp-media/uploads/2017/05/golf-club.jpg

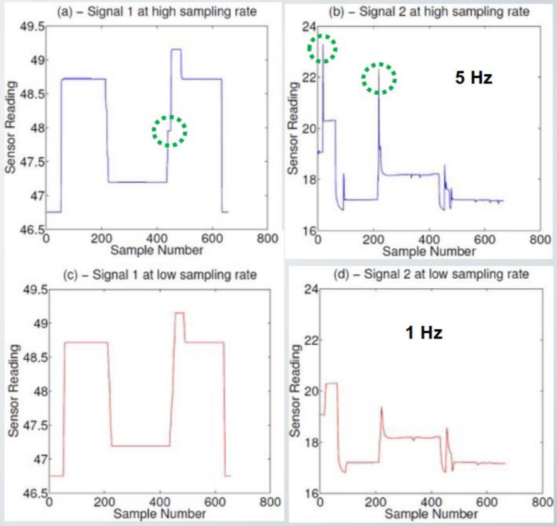
Data Overload in Semiconductor Manufacturing Systems





https://electroiq.com/2017/06/fast-and-precise-surface-measurement-of-back-grinding-silicon-wafers/

- Advancements in data collection lead to more sensors, higher sampling rates
- A modern fab has well over 100K sensors streaming data at 10Hz (with possibilities to dramatically increase sampling rates)
- Fully automatic data management, curation and mining becomes a necessity and a challenge
- Direct application of machine learning from computer science has not given satisfactory results



Landscape of Data Analytics in Industry

Applications

- Operations modeling and optimization (evolution)
- System and process autonomy (resilience)
- Modeling & assessment of system performance (self-awareness)

Physical Data Analytics

https://resourcecenter.ieee-pels.org/webinars/PELSWEB050917v.html (Dr. H. Hamman, IBM Watson Research Center)

- Traditional operations research & industrial engineering
- Traditional estimation & control theory
- Traditional machine & process modeling & monitoring

Methods

- Advanced statistics, artificial intelligence and machine learning (success in computer science, social networks)
- Physically inspired signal processing & signature extraction coupled with advanced statistics, artificial intelligence & machine learning
- Physically plausible/analytically tractable models coupled with advanced statistics, artificial intelligence & machine learning
- Methods dominated by first-principles based physics & analytic tractability

Recent Examples of Physical Data Analytics Applied to Modeling, Monitoring and Control of Semiconductor Manufacturing Processes & Systems

Fusion of physics and data analytics for modeling, monitoring and control of complex systems

Data Processing and Modeling

- Dynamics-inspired processing and curation of sensor data from semiconductor manufacturing tools
- Advanced dynamic modeling for Virtual Metrology (VM) in semiconductor manufacturing
  – Plasma Enhanced Chemical Deposition (PECVD) Processes
  – Critical Dimensions (CD) in etch processes

Monitoring

- Transfer-learning based condition monitoring of e-beam based mask making processes
- Hidden Markov Model (HMM) based monitoring of plasma enhanced chemical vapor deposition (PECVD) processes
- Vibrations based monitoring of equipment in semiconductor manufacturing
  – Detection of particle generating features in material handling systems
  – Monitoring of slit valves

Control

- Robust control of overlay and stack-up overlay errors in photo-lithography processes
- Integrated maintenance and production decision-making in semiconductor manufacturing systems

The term “physical analytics” introduced by Dr. H. Hamman from IBM Watson Research Center https://resourcecenter.ieee-pels.org/webinars/PELSWEB050917v.html

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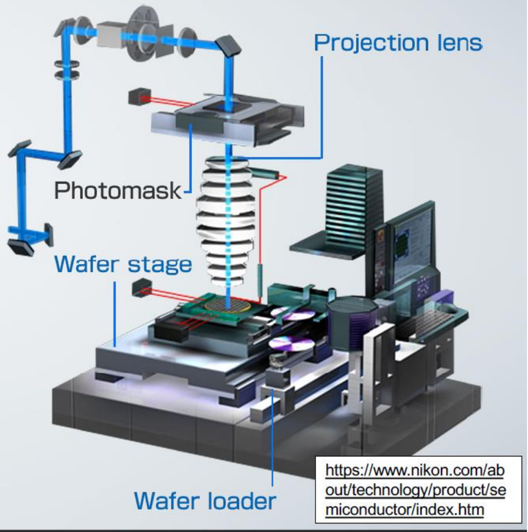
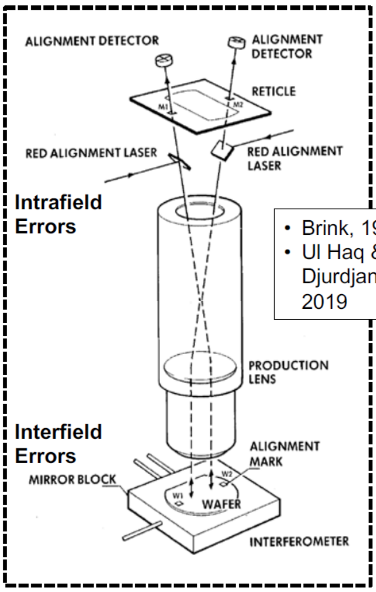
Lithography Overlay for Patterning of Integrated Circuitry (IC)

- Lithography is the "holy grail" of integrated circuitry (IC) manufacturing
- 33% of wafer manufacturing costs are consumed by lithography
- Alignment of successive layers within the device directly determines performance of a chip
- Alignment between successive layers is referred to as *overlay*, while that between non-adjacent layers is referred to as *stack-up overlay*
- Requirements on overlay accuracy keep growing (Int'l. Technology Roadmap for Semiconductors, 2009)

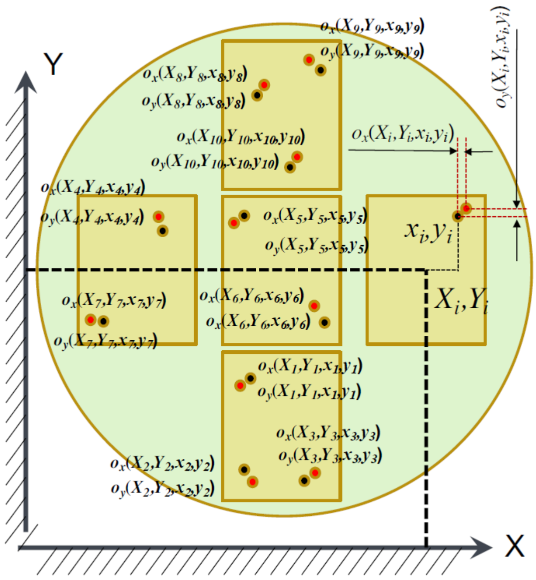


https://www.nikon.com/about/technology/product/semiconductor/index.htm

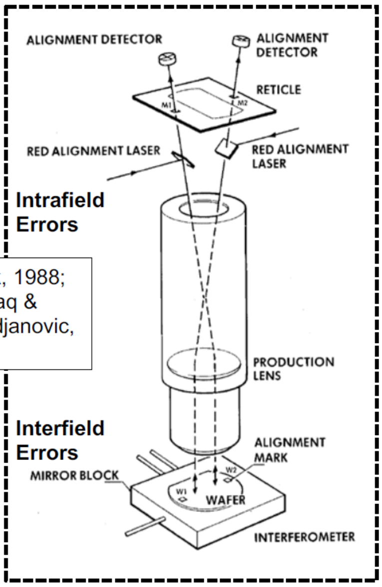
Characterization of Overlay Errors



- Brink, 1988;
- Ul Haq & Djurdjanovic, 2019



Zernike Polynomial based Models of Overlay Errors



- Brink, 1988;
- Ul Haq & Djurdjanovic, 2019

$$o_x(X_i,Y_i,x_i,y_i) = T_x - R_xY_i + M_xX_i + B_xY_i^2 - r_x y_i + m_x x_i - t_x x_i^2 - v_x x_i y_i + w_x y_i^2 + d_{3x} x_i\left(x_i^2+y_i^2\right) + d_{5x} x_i\left(x_i^2+y_i^2\right)^2 + \varepsilon_x(X_i,Y_i,x_i,y_i)$$

$$o_y(X_i,Y_i,x_i,y_i) = T_y + R_yX_i + M_yY_i + B_yX_i^2 + r_y x_i + m_y y_i - t_y y_i^2 - v_y x_i y_i + w_y x_i^2 + d_{3y} y_i\left(x_i^2+y_i^2\right) + d_{5y} y_i\left(x_i^2+y_i^2\right)^2 + \varepsilon_y(X_i,Y_i,x_i,y_i)$$

Inter-field tool parameters

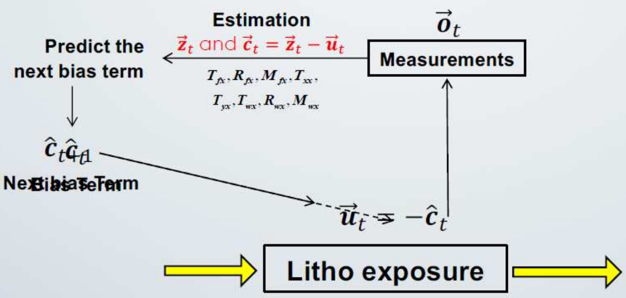
- T_x, T_y Translation errors
- R_x, R_y Wafer rotation
- M_x, M_y Wafer magnification
- B_x, B_y Block mirror imperfections

Intra-field tool parameters

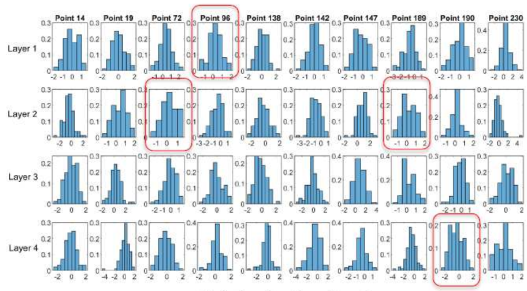
- r_x, r_y Field rotation
- m_x, m_y Lens magnification
- w_x, w_y Wedge distortion
- t_x, t_y, v_x, v_y Trapezoidal distortion (reticle tilt)
- $d_{3x}, d_{3y}, d_{5x}, d_{5y}$ Higher order symmetrical distortion

Traditional Run-to-Run Control of Overlay Errors

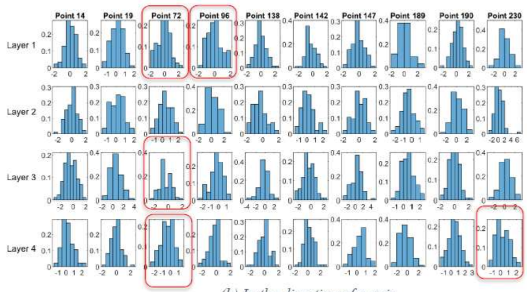
- Use the control command $\vec{u}_t$ to *counteract what we think bias* terms $\vec{c}_t$ are by setting $\vec{u}_t = -\hat{c}_t$, where $\hat{c}_t$ is the estimated (*predicted*) bias $\vec{c}_t$ based on the previously observed biases $\vec{c}_0, \vec{c}_1, \vec{c}_2, \dots, \vec{c}_{t-1}$
- After pattern on wafer number t is produced, take measurements of overlay errors $\vec{o}_t$ for that wafer
- Based on those measurements, use the overlay model to estimate **what actual process parameters** $\vec{z}_t$ (what actual translation *T*, rotation *R*, magnification M and so on) were achieved. This tells us what actual bias occurred at wafer *t* by $\vec{c}_t = \vec{z}_t - \vec{u}_t$.
- Estimate (predict) the bias term $\vec{c}_{t+1}$ for the next wafer (wafer number *t*+1) using some prediction method (e.g. Kalman filter or EWMA method)



Is This Normal Independent Identically Distributed (NIID)?

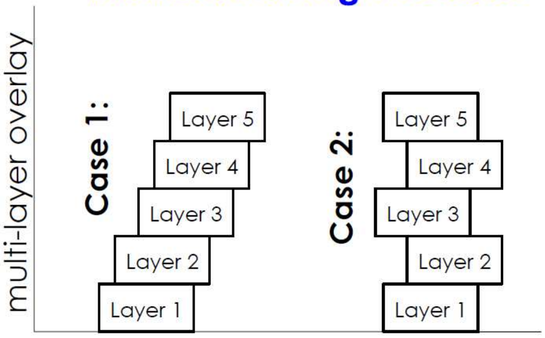


(a) In the direction of x-axis



(b) In the direction of y-axis

Lithography is a Multistage Manufacturing Process



$s_x(k) = s_x(k-1) + o_x(k),\ s_y(k) = s_y(k-1) + o_y(k),$ represents the stack-up overlay errors up to k^{th} layer (Yu & Qin, 2007)

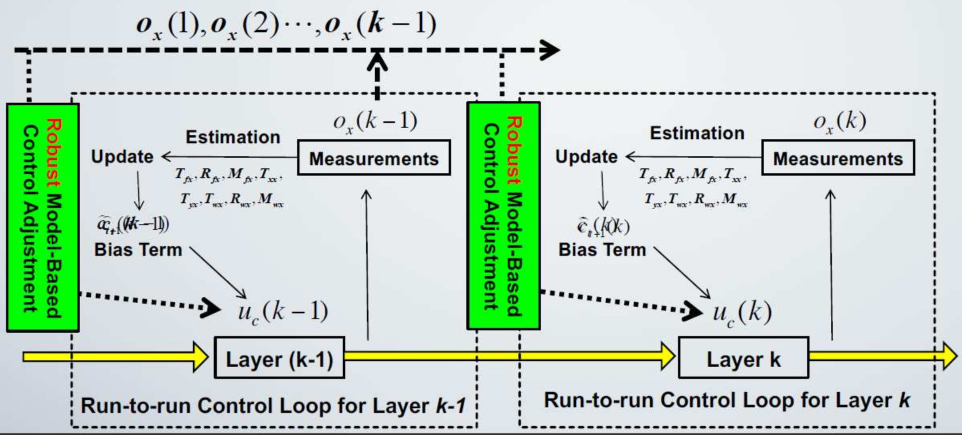
In our work we assume that:

- **Model parameters are not perfectly known**
- **Noise characteristics can follow any distribution & can be dependent**

Robust Multi-layer Overlay Control

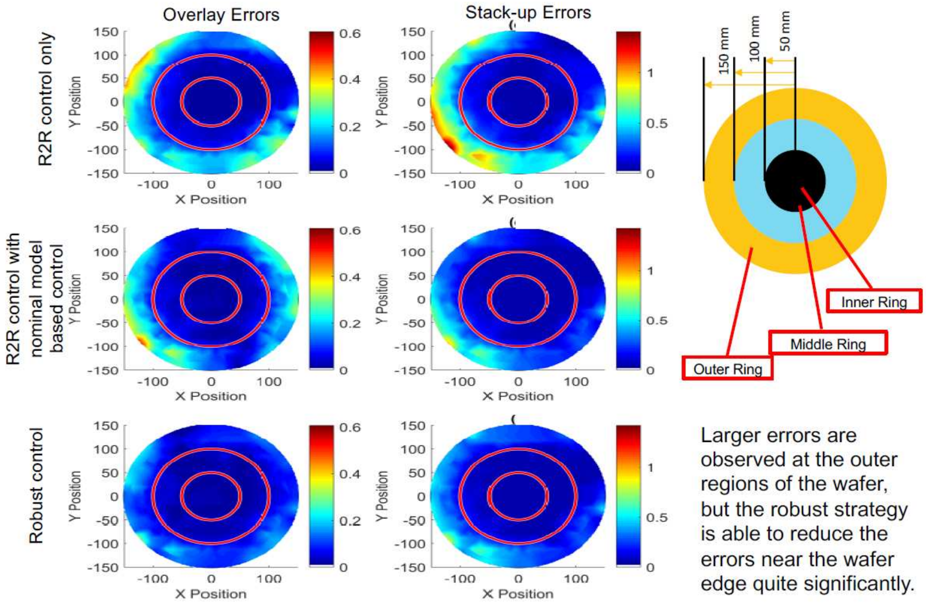
At each layer *k*

- Obtain the previous overlay errors $o_x(1), o_x(2)\cdots, o_x(k-1)$ for that wafer *t*
- Calculate the optimal control $u_c(k)$ based on the previous overlay error information and bias term $\hat{c}_t(k)$
- Run to run control loop of k^{th} layer (update the bias term $\hat{c}_t(k)$ to $\hat{c}_{t+1}(k)$)



- *A. Ul Haq* & D. Djurdjanovic, "Robust Control of Overlay Errors in Photolithography Processes," *IEEE Transactions on Semiconductor Manufacturing*, 32/3, pp. 320-333, 2019.
- *H. Zhang*, T.-H. Feng & D. Djurdjanovic, "Dynamic Down-Selection of Measurement Markers for Optimized Robust Control of Overlay Errors in Photolithography Processes," *IEEE Transactions on Semiconductor Manufacturing*, 35/2, pp. 241-255, 2022

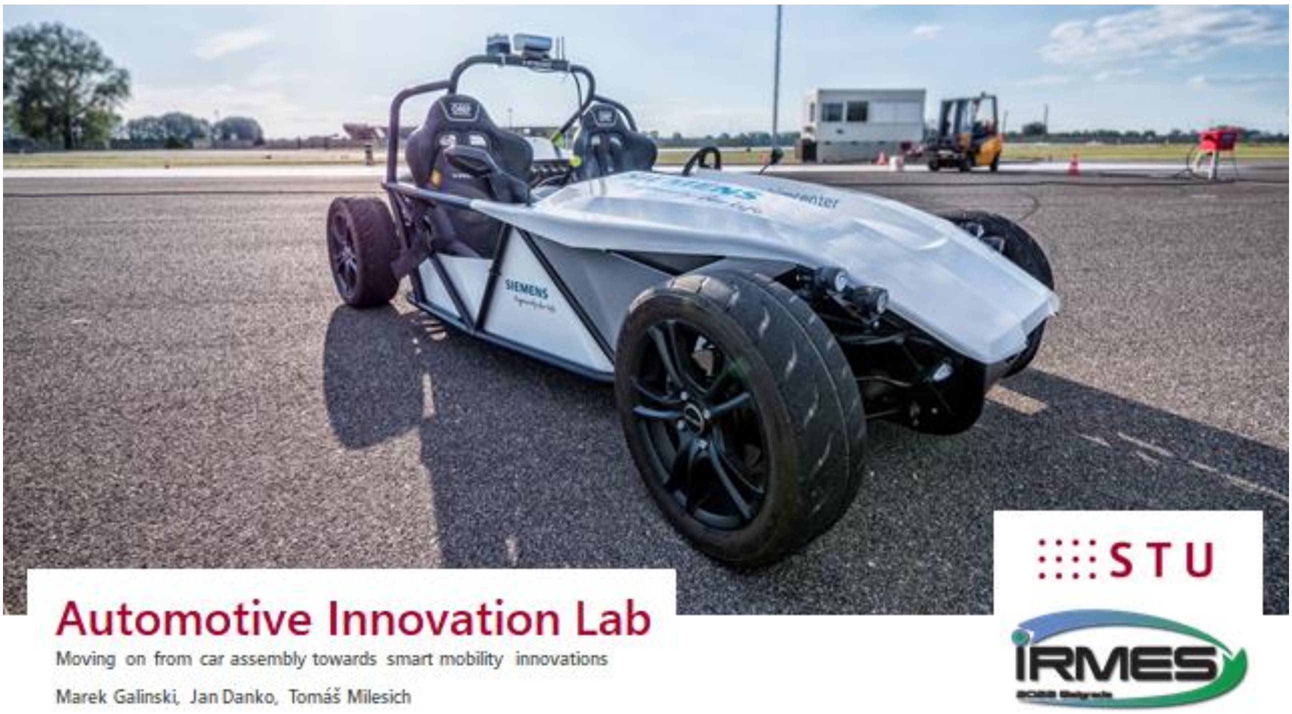
Performance Evaluated using Model and Data from a Process in a 300 mm Fab



Larger errors are observed at the outer regions of the wafer, but the robust strategy is able to reduce the errors near the wafer edge quite significantly.

- Both the range of stack-up errors and their mean values are reduced for almost all layers and noise levels, compared to the traditional run-to-run strategy
- Increased uncertainties in the model/noise increase the importance of using robust control
- **Opportunity to dramatically reduce measurements while maintaining control of overlay errors**

AUTOMOTIVE INNOVATION LAB
Marek GALINSKI, Jan DANKO, Tomáš MILESICH



INTRODUCTION

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STU
SjF

Tomáš Milesich, PhD.

Assistant professor - Department of Automobiles, Ships and Combustion Engines, Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava

2

CHALLENGE

Is it possible, to build a full-size autonomous car without any research grants, investors and carry passengers in it here, in Slovakia?

3

COOPERATION

STU SjF
SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE
STROJNÍCKA FAKULTA

STU FIIT
SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE
FAKULTA INFORMATIKY A INFORMAČNÝCH TECHNOLÓGIÍ

STU SvF
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STAVEBNÁ FAKULTA

SIEMENS

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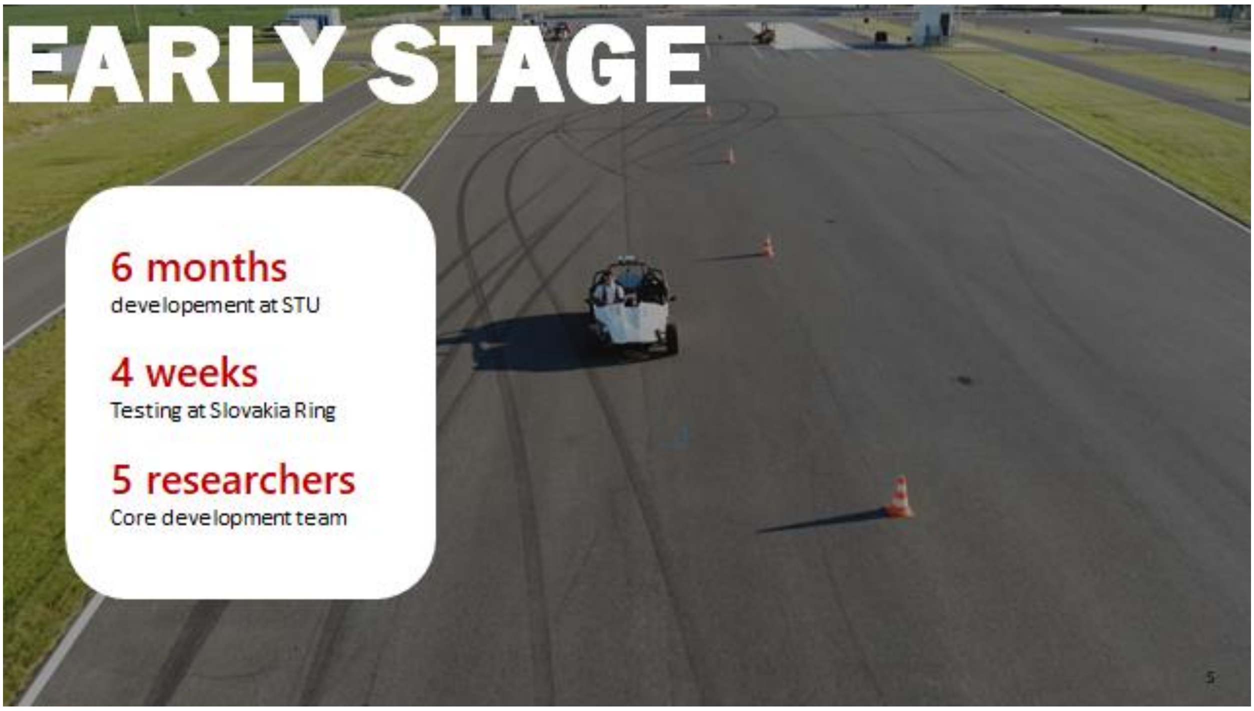

SHOWTIME

14.1 mm
Navigation accuracy

70 km/h
Driving in ADAS mode

100 m
LiDar obstacle detection

LTE
live connectivity

OBJECTIVES

7

OBJECTIVES

To advance cross domain research on intelligent safety & ADAS systems in cooperation with industry.

8

OBJECTIVES

To equip vehicle with set of robust and resilient sensors to help driver in detecting situations beyond human capacity.

OBJECTIVES

To empower V2x connectivity approaches based on 5G & Edge Computing to predict potentially dangerous situations on roads avoiding fatalities

SHOWTIME

12

SHOWTIME

13

The 10th International Scientific Conference IRMES 2022 "Machine design in the context of Industry 4.0 - Intelligent products", 26. May 2022, Belgrade, Serbia.

SMART PRODUCTS – STATE OF THE ART

- Review paper -

by

Vidosav Majstorović, Tanja Lazović, Žarko Mišković, Radivoje Mitrović

Presenting author: Prof. Dr. Vidosav D. MAJSTOROVIĆ, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, SERBIA.

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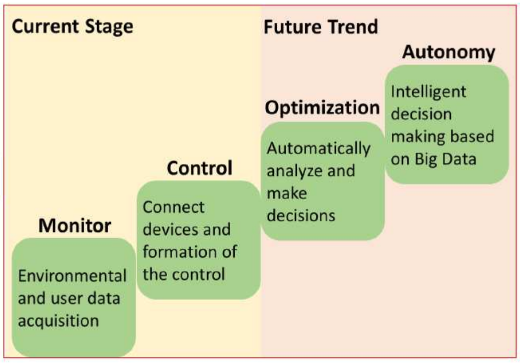
FRAMEWORK OF INDUSTRY 4.0 AND SMART PRODUCTS

1



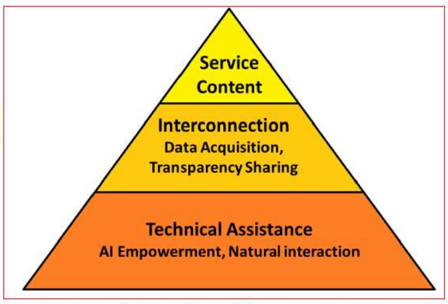
Intelligent products in the context of Industry 4.0

2

Sensor module		Communication module
Operating system module		
Power module	Structural component module	Extended function module

Basic structure (modules) of intelligent products

3



Basic principles of intelligent product design

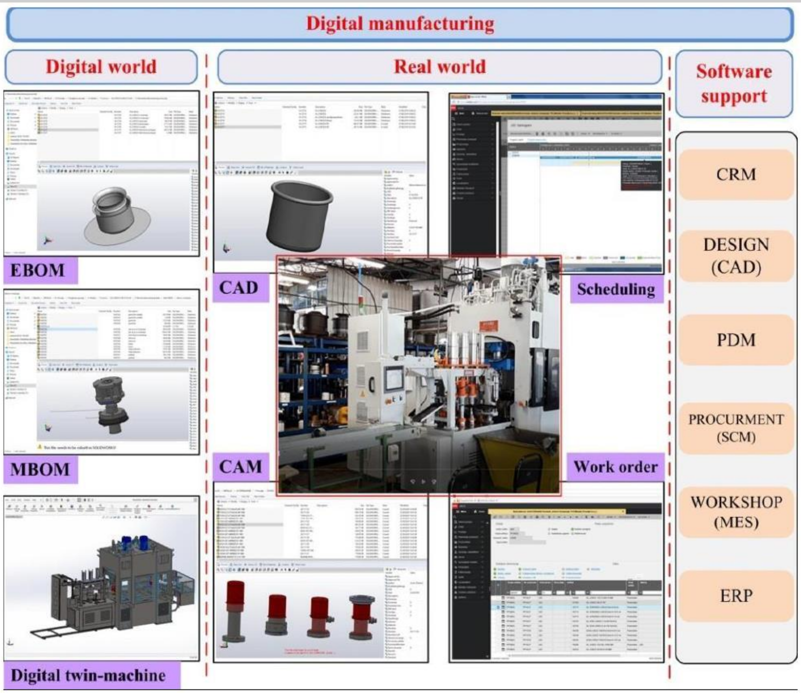
Source: Jiarui Wang, et al., Research on the Design Principles for Intelligent Products, Springer Nature Switzerland AG 2019, A. Marcus and W. Wang (Eds.): HCII 2019, LNCS 11583, pp. 351–367, 2019. https://doi.org/10.1007/978-3-030-23570-3_26.

	Level 1- Digital (to the 2000)	Level 2 – Connected (2000-2010)	Level 3 - Responsive (2010-2020)	Level 4 – Intelligent / Industry 4.0 (after 2020)
Hardware & Software support	Basic hardware Software for basic operating	Basic hardware Connectors Sotware for communication	Basic hardware Connectors Sensors & Actuators Sotware for define pre-sensing and responding logic (SRL) and programmable SRL	Basic hardware Connectors Sensors & Actuators Sotware for define pre-sensing and responding logic (SRL) and programmable SRL AI software for learning, improving and anticipating
Capability	ITT Equipped Data storage Data processing &analysis Data provision & transmission	+ Unique identification Networking & Connectivity Communication & Information Exchange Interaction & Cooperation	+ Sensing Real time context – awarness Reactivity & Adaptability Automated Actuation Functionality & Customization	+ Reasoning & Decision making Autonomy & Self-management Proactivity
Application (functions & services)	Predefined input and output operations (digital camera) Basic settings (radio station or alarm setting, hi-fi system) Entering, storing and displaying of information (Apply iPod) Car digital panel	Tracking services (Smart meter) Dispersed funcionality (Samsung (Philips) Hue Lighting System) Remote control and monitoring (wirelees printer) Infotainment (Audi connect)	IFTTT routines (Amazon Echo) Rule-based skill and actions (Gougle Home actions) Reactive actions (car lane assist) Deterministic automated action (Amazon Dash Shelf) Location & data-based services or navigation tasks (route optimization) Performance tracking (Apple Watch)	Complex context-based servicies (NEST Learning Thermostat) Procative services (anticipatory services in the AI CON car) Complex learning-based and self-organizing autonomus actions (driverless vehicles)

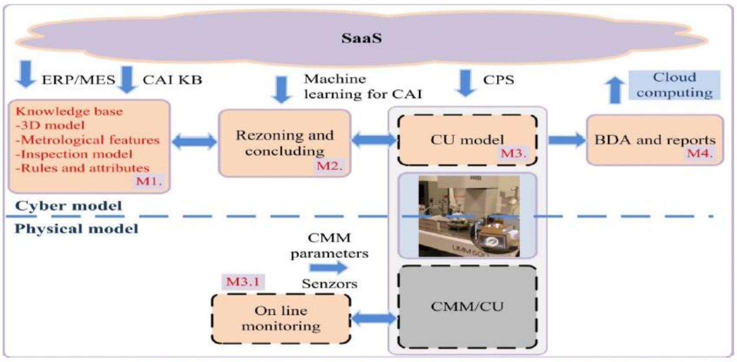
Source: Stefan Raff, et al, Smart Products: Conceptual Review, Synthesis, and Research Directions, J Prod Innov. Manag. 2020; 37(5):379–404, www.doi:10.1111/jpim.12544.

Levels of development of intelligent products

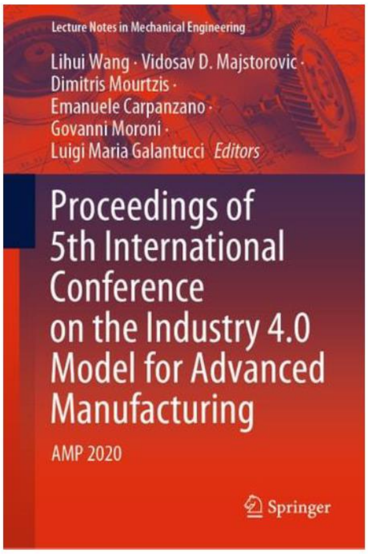
INDUSTRY 4.0 IN SERBIA – RESEARCH AND PRACTICE SUPPORT OF MEF

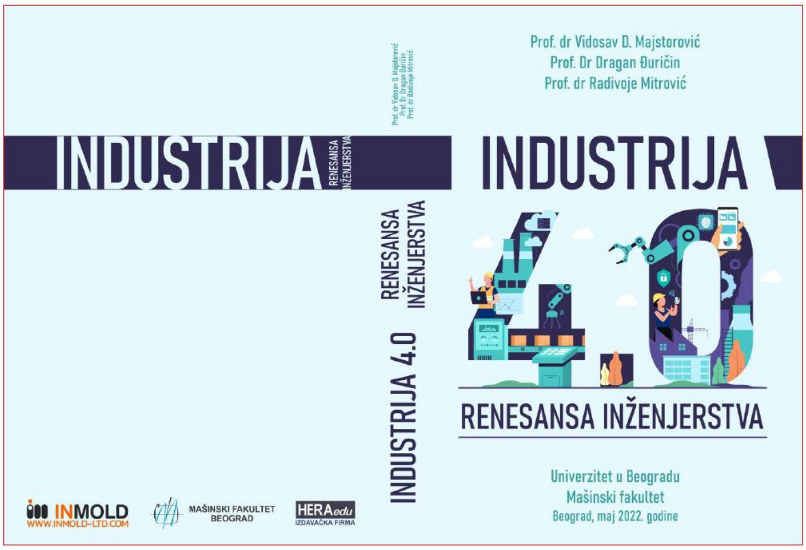


INDUSTRY 4.0 IN SERBIA – RESEARCH AND PRACTICE SUPPORT OF MEF



NEW EDITIONS





INVITED LECTURES

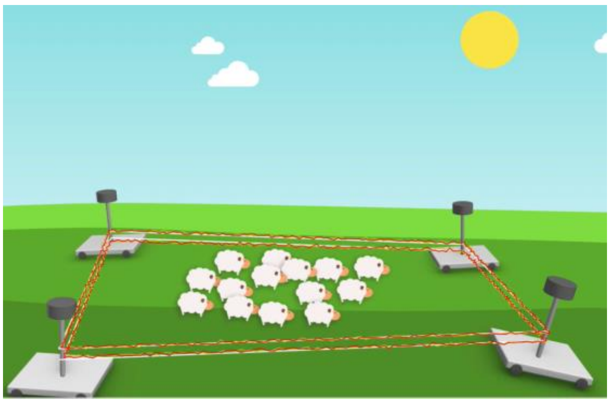
10th International Scientific Conference
IRMES 2022
"Machine design in the context of Industry 4.0 – Intelligent products"
26 May 2022, Belgrade, Serbia

DESIGN OF ROBOTIC SYSTEM FOR AUTOMATED ANIMAL HUSBANDRY AND GRAZING

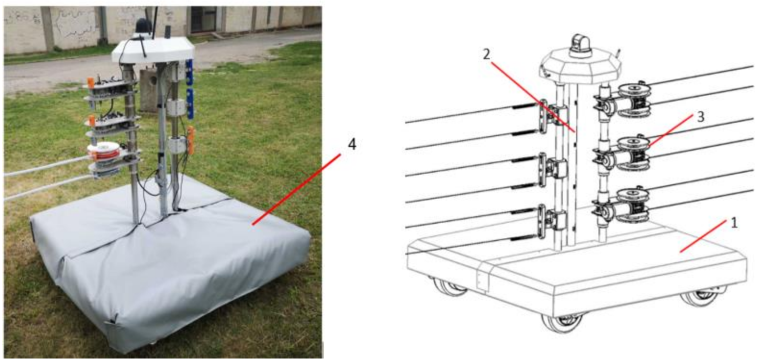
Milan BANIĆ
Miloš SIMONOVIĆ
Aleksandar MILTENOVIĆ

Abstract: *The Industry 4.0 trend is transforming all industries, including the agricultural domain. Agriculture is a sector in which there is a constant decrease in labour force and increase in needs for agricultural products. RoboShepherd solution is developed according to the Industry 4.0 technologies and represent an example of an intelligent product that can become a successful market solution. RoboShepherd is an autonomous herding and pasturing system where a robotic shepherd takes the form of a programmable, intelligent electric fence, which surrounds the livestock during grazing and herding to the pasture. The system is a movable enclosure, which, by moving, directs the movement of the animals within the enclosure and along a predefined route. In this paper are presented main aspects of an innovative solution for easier shepherding and monitoring of animals.*

Keywords: *robotics; agriculture; herding; grazing*



RoboShepherd – automated livestock driving and pasturing system



RoboShepherd robotic unit: photo on the left side, CAD model on the right

10th International Scientific Conference
IRMES 2022
"Machine design in the context of Industry 4.0 – Intelligent products"
26 May 2022, Belgrade, Serbia

APPLICATION OF THE MATLAB TOOLBOX "SIMSCAPE MULTIBODY" IN THE ANALYSIS OF THE MOVEMENT OF COMPLEX MECHANISMS

Radoslav TOMOVIĆ
Mirjana KOPRIVICA

Abstract: *One of the key principles on which the machine design within the Industry 4.0 concept is based on the simulation of the work and movement of complex mechanical systems and mechanisms. In order to achieve this, it is necessary to use efficient software tools. This paper presents the application of the "Simscape Multibody" toolbox developed within the Matlab software platform. Using the software, an analysis of the movement of Jansen's eight-membered mechanism was made.*

Keywords: *Matlab, Simscape multibody, walking mechanism, Jansen, kinematics, robot*

1. INTRODUCTION

Global market liberalization and continual energy deficit are the basic characteristics of world economic movements from the end of the previous century and the beginning of this century. Global liberalization has increased competition, which has forced manufacturers to produce quality and cheap and to meet customer requirements, even going to their individual desires. Manufacturers invest huge resources in the research and development of new and better products and technologies. The lack of energy conditioned the need to find new energy sources, but also the need for rationalization and optimization of systems that produce and spend energy [1]. Depending on the specific needs, which corresponds to certain working conditions, certain user requirements, the market offers a wide range of products, different types and different quality, which require excellent performance, high efficiency, good aesthetic and ergonomic features. Because of the current problem of energy shortages and protection and preservation of the environment and safety at work, the product requires as much energy saving (reduction of friction and power losses), less noise, as well as more compact design (weight reduction and material savings) [2].
The fulfillment of these requirements is conditioned by the trend of improving the process of product design and construction in order to increase efficiency, reducing the time required for product development, increasing use of modern software for design, calculation and simulation and introduction of teamwork and group dynamics.
The general digitalization and development of IT technology has produced a series of radical transformations in all stages of product life, even in the design and construction phases. Research and development of innovation, as well as the rapid tempo of implementation, and especially digitalization and automation, have the main role of shaping future industrial business, designated as the fourth industrial revolution or industry 4.0. It is built on the foundations of artificial intelligence (AI), storage and date processing in the cloud (CC) and analysis of large date sets (BDA), using machines – cyber physical systems (CPS) [3].
Industry 4.0 requires the development and design of new products to the new rapid requirements of the market, which seeks to reduce development and design time while accelerating production, all with the aim of making a final product in as soon as possible. The first technology which has fundamentally changed the process of product development and design was Computer Aided Design (CAD) technology [4]. By developing modern CAD program packages in early 1990s, among other things, enabled designers and engineers to make realistic representations of their ideas, but also to make various simulations to analyse the behaviour of the system in a real environment. CAD technologies have solved the problem of product visualization, as well as simulations and behavioural analysis in working conditions. Prototype and laboratory testing of prototypes is often very expensive and often causes many good ideas to never see the light of day, because their creators do not have enough funds to invest in the development of their product [5].
In this paper, the application of the "Simscape Multibody" development tool within the Matlab software platform, for an analysis of an eight-membered mechanism designed by Theo Jansen in 2005. [6]. Using the Simscape Multibody software, a model of the Jansen mechanism was made using graphical components, by

decomposing the actual system of rigid body, fixed joints, drives, sensors input, etc.

2. JANSEN MECHANISM

Theo Jansen designed one of the most popular walking mechanism, which he called the Jansen mechanism. It is a plane mechanism with one degree of freedom of movement consisting of eight members. Members of this mechanism are five levers, two triangles and supports [7].

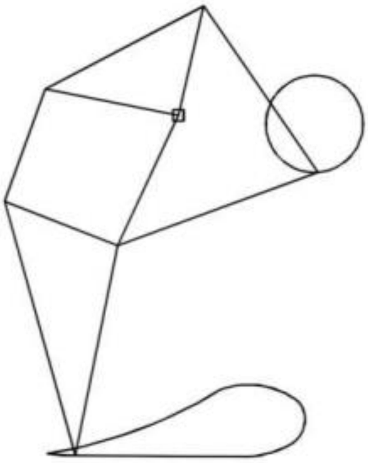


Fig. 1. Jansen mechanism [8]

3. MATLAB SIMSCAPE MULTIBODY

The Simscape Multibody toolbox within the Matlab programming language provides space to simulate multiple interconnected bodies for 3D mechanical systems such as robots. Using the blocks that represent bodies, joints, restrictions and sensors, it is possible to model a multibody system. Within this toolbox, the simulation of movement of the mechanism is obtained (Fig 2).

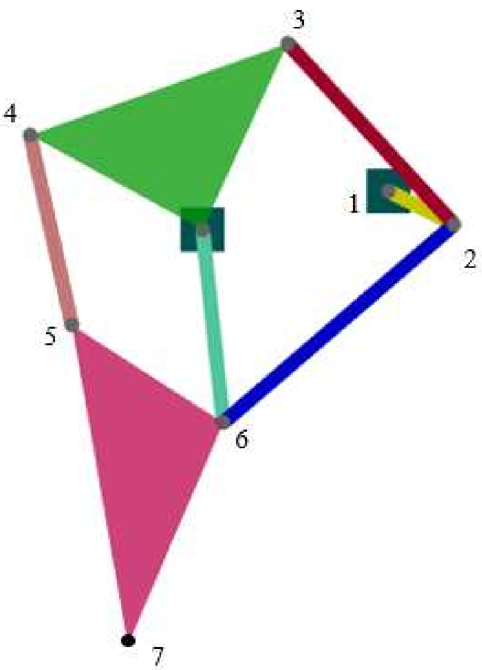


Fig. 2. Jansen's mechanism within the Simscape Multibody toolbox at Matlab

4. SIMSCAPE MULTIBODY MODEL OF JANSEN MECHANISM

4.1. Kinematics of Jansen mechanism

The mechanism scheme is showen in Figure 3 and the dimensions of the members are given in Table 1.

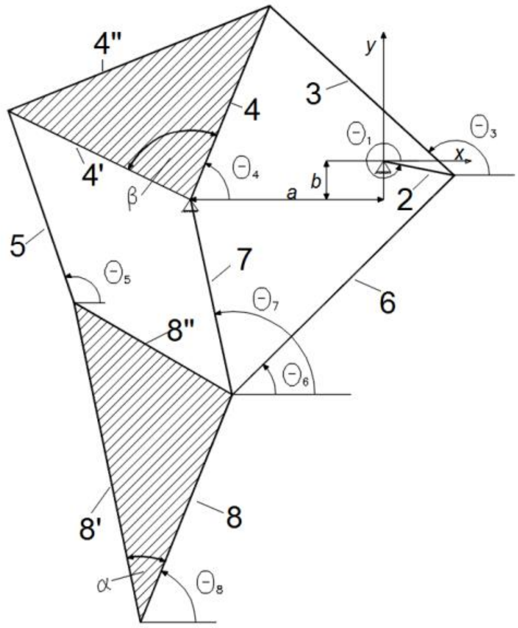


Fig. 3. The scheme of Jansen mechanism [8]

The table shows the dimensions required to model this mechanism within Matlab's Multibody Simscape toolbox.

Table 1. Dimensions of mechanism members

l_2	15 mm
l_3	50 mm
l_4	41.5 mm
l_4'	40.1 mm
l_4''	55.8 mm
l_5	39.4 mm
l_6	61.9 mm
l_7	39.3 mm
l_8	49 mm
l_8'	65.7 mm
l_8''	36.7 mm
a	38 mm
b	7.8 mm
α	33.475°
β	86.268°

In order to perform kinematic analysis by numerical method, it is first necessary to determine the equations of loop [8, 9, 10].

Between members 2, 3 and 4 is first loop (Fig 4). Loop equation is:

$$l_2e^{i\theta_2} + l_3e^{i\theta_3} + (a+bi) = l_4e^{i\theta_4} \quad (1)$$

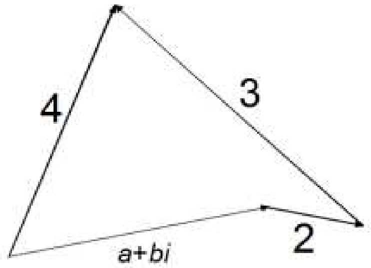


Fig. 4. First vector loop [8]

Between members 3, 4, 6 and 7 is second vector loop (Fig 5).

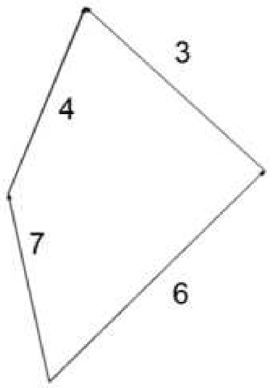


Fig. 5. Second vector loop [8]

Equation of second loop:

$$l_6e^{i\theta_6} + l_3e^{i\theta_3} = l_4e^{i\theta_4} + l_7e^{i\theta_7} \quad (2)$$

Third loop is between the members 4', 5, 7, 8 and 8' (Fig 6).

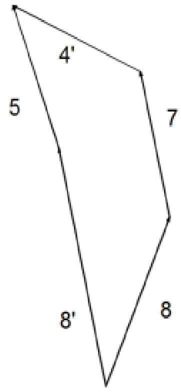


Fig. 6. Third vector loop [8]

Equation of third loop:

$$l_8e^{i\theta_8} + l_7e^{i\theta_7} + l_4\,'e^{i(\theta_4+\alpha)} = l_8\,'e^{i(\theta_8+\beta)} + l_5e^{i\theta_5} \quad (3)$$

When projections on real and imaginary axes of these loop are differentiated and written in matrix form, we get Jakobijan's matrix [8].

$$J = \begin{bmatrix} -l_3\sin(\theta_3) & l_4\sin(\theta_4) & 0 & 0 & 0 & 0 \\ l_3\cos(\theta_3) & -l_4\cos(\theta_4) & 0 & 0 & 0 & 0 \\ -l_3\sin(\theta_3) & l_4\sin(\theta_4) & 0 & -l_6\sin(\theta_6) & l_7\sin(\theta_7) & 0 \\ l_3\cos(\theta_3) & -l_4\cos(\theta_4) & 0 & l_6\cos(\theta_6) & -l_7\cos(\theta_7) & 0 \\ 0 & -l_4\,'\sin(\theta_4\,'+\alpha) & -l_5\sin(\theta_5) & 0 & -l_7\sin(\theta_7) & -l_8\sin(\theta_8)-l_8\,'\sin(\theta_8\,'+\beta) \\ 0 & l_4\,'\cos(\theta_4\,'+\alpha) & l_5\cos(\theta_5) & 0 & l_7\cos(\theta_7) & -l_8\cos(\theta_8)-l_8\,'\cos(\theta_8\,'+\beta) \end{bmatrix}$$

Velocity is obtained through equation: [8]

$$J\cdot\left[\dot{q}_g\right] = -\left[\frac{\partial k}{\partial q_p}\right]\cdot\dot{q}_p \Rightarrow \left[\dot{q}_g\right] = -J^{-1}\cdot\left[\frac{\partial k}{\partial q_p}\right]\cdot\dot{q}_p \quad (4)$$

Where:
q_p – drive member
q_g – driven members [8].

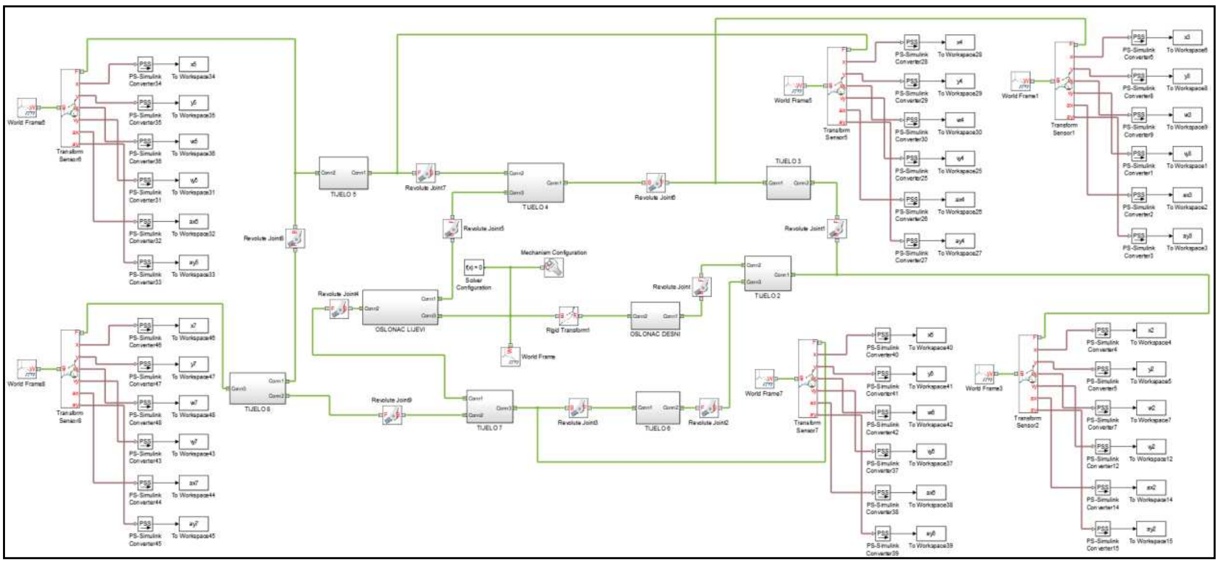


Fig. 7. Block diagram of Jansen mechanism

By differentiating this equation over time, the acceleration equation is obtained [8]:

$$\left[\frac{\partial^2 k}{\partial q_p^2}\;\frac{\partial^2 k}{\partial q_g^2}\right]\cdot\begin{bmatrix}\dot{q}_p^2\\ \dot{q}_g^2\end{bmatrix}+2\cdot\left[\frac{\partial^2 k}{\partial q_p \partial q_g}\right]\begin{bmatrix}\dot{q}_p\\ \dot{q}_g\end{bmatrix}+\left[\frac{\partial^2 k}{\partial q_g^2}\right]\cdot\left[\ddot{q}_g\right]=0 \quad (5)$$

The kinematic analysis using Multibody Simscape toolbox is based on creating a model via block diagram. The block diagram is created by inserting blocks that represent the required output data (Fig 7).

Coordinate diagrams, velocity and acceleration of all joints of the mechanism are given in Figure 8.

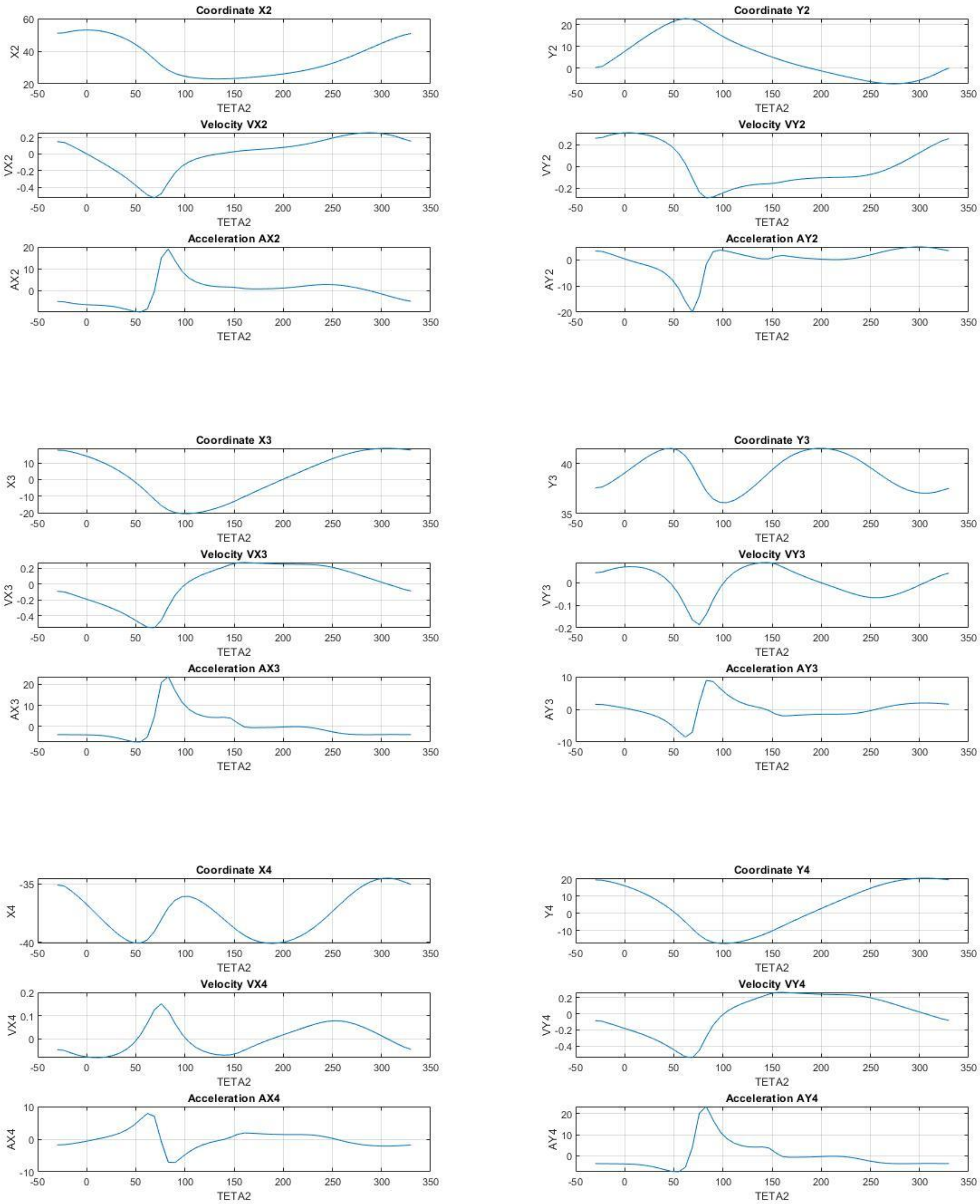


Fig. 8. a) Velocity and acceleration of joints of the mechanism

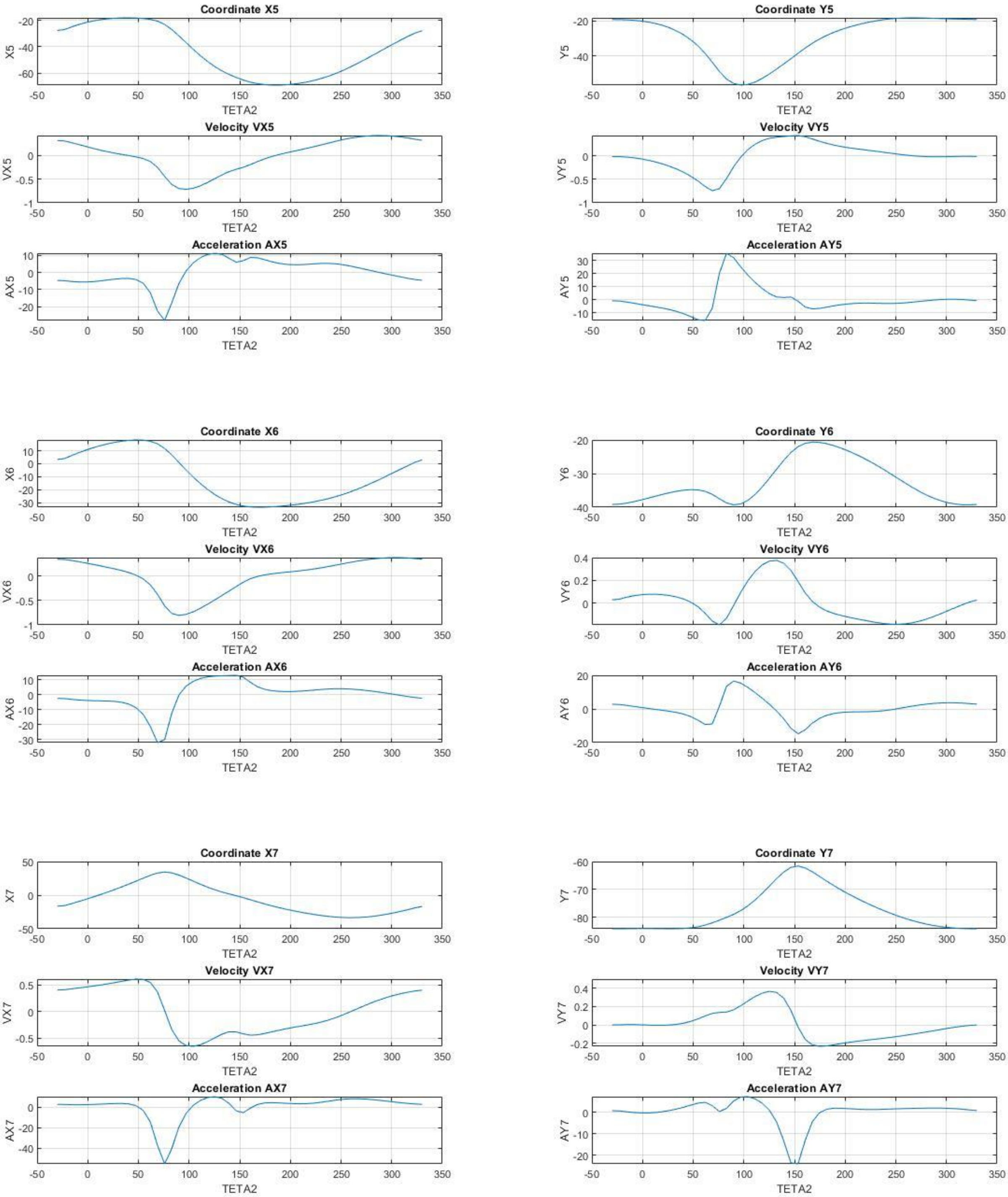


Fig. 8. b) Velocity and acceleration of joints of the mechanism

4.2. Locus

The locus of Jansen mechanism is a closed curved line that makes the leg of the mechanism when rotating the drive member. The main locus vector has the beginning in support 1(Figure 2) and the end in point 7 (Figure 2). Vector projection on *x* and *y* axis give the locus of the mechanism (Figure 9).

In addition to the path of point 7, the paths of all joints of the mechanism are determined (Figure 10).

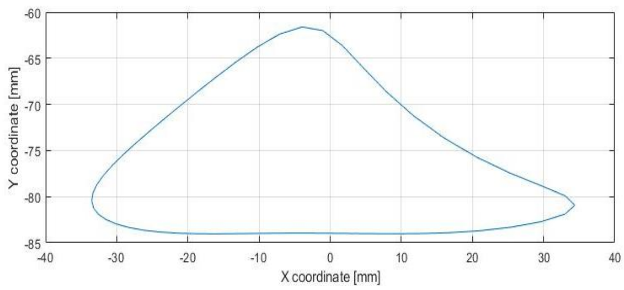


Fig. 9. Locus of the Jansen mechanism

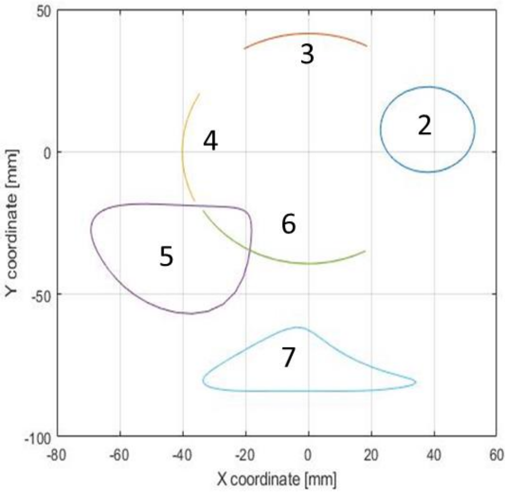


Fig. 10. Movement of all Jansen's mechanism joints

5. CONCLUSION

Based on the analysis of the movement of a eight-member Jansen's mechanism, the following can be concluded:

- The Matlab toolbox used in this paper is suitable and practical for a kinematic analysis of complex mechanical systems and mechanisms.
- The analysis made in this paper showed the high potential of the developed approach based on tools for motion simulation and kinematics analysis of complex mechanical systems, which is primarily reflected in the very simple generating an equations of motion, quick and easy obtaining relevant parameters describing that movement (path, velocity and acceleration of characteristic points and members of the mechanism).
- The application of toolbox for simulation of movement and kinematics of mechanisms contributes to significant acceleration of the processes of new products development, as one of the most important elements of industry 4.0. The time available to designers to develop new products is shortening every day. Therefore, the application of effective software for simulation of movement of complex mechanisms not only a the issue of modernization, but also an imperative of survival in a demanding global market.
- Matlab Simscape Multibody is practical for use and provides the possibility of obtaining a large number of different data, visual display of results and easy correction of mechanism parameters at any time in accordance with the needs and requirements set to the project assignment.

REFERENCES

[1] Tomović, R.: *Osnove konstruisanja,* Univerzitet Crne Gore, Mašinski fakultet Podgorica, ISBN 978-9940-527-44-0., 2015

[2] Tomović, R.: *Primjena savremenih metoda konstruisanja u razvoju proizvoda mašinske industrije,* Univerzitet Crne Gore, Mašinski fakultet u Podgorici, Crna Gora, 2000.

[3] Mitrović, R, Majstorović, V., Mišković Ž.: Razvoj i primena Industrije 4.0 u Srbiji, *Proceedings of conference Aplikacija Industrije 4.0 – prilika za novi iskorak u svim industrijskim granama*, 14. aprila 2022, Sarajevo, pp 3-14, ISBN 978-9926-410-75-9, Akademija nauka i umjetnosti Bosne i Hercegovine, 2022.

[4] Boyer, B., Balleyguier, C., Granat, O., & Pharaboz, C.: CAD in questions/answers: Review of the literature, *European journal of radiology,* Vol:69, No 1, pp. 24-33., 2009.

[5] Muminović, A., Pandžić, A., Pervan, N., Delić, M.: Razvoj i dizajn proizvoda u sklopu Industrije 4.0: od brze izrade prototipova do aditivne proizvodnje, *Proceedings of conference Aplikacija Industrije 4.0 – prilika za novi iskorak u svim industrijskim granama*, 14. aprila 2022, Sarajevo, pp 69-80, ISBN 978-9926-410-75-9, Akademija nauka i umjetnosti Bosne i Hercegovine, 2022.

[6] Zhou, J., Mohsenizadeh, M.: Kinematic Analysis and Simulation of Theo Jansen Mechanism*, in Early Career Technical Conference,* Birmingham, 2015.

[7] Vujošević, V.: *Istraživanje mogućnosti za razvoj hodajućih mašina na bazi Jansenovog mehanizma*, Univerzitet Crne Gore, Mašinski fakultet u Podgorici, 2020.

[8] Mumović, M., Tomović, A., Vujošević, V., Tomović, R.: Development of walking platform of robot based on Jansen mechanism, *in XIV International SAUM Conference*, Nis, 2018.

[9] Tomović R., Vujošević V., Mumović M., Tomović A.: Kinematic model of robot based on Jansen mechanism, in *4nd International scientific conference „Conference on Mechanical Engineering Technologies and Applications" COMETa 2018*, Jahorina-BiH, November 2018, pp. 261-268, ISBN 978-99976-719-4-3, 2018.

[10] Vujošević V., Mumović M., Tomović A., Tomović R.: Robot based on walking Jansen mechanism, *IOP Conf. Series: Materials Science and Engineering 393*, 012109, doi:10.1088/1757-899X/393/1/012109, 2018.

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10th International Scientific Conference
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DESIGN PROCESS OF A FULLY ELECTRIC VACUUM SWEEPER

Ile MIRCHESKI

Abstract: *The street sweepers are machines which are an important segment for maintaining a clean city. The modern metropolis is under severe stress from uncontrolled human activity. The aim of this paper is to present the design process of a fully electric vacuum sweeper equipped with revolutionary air-recirculation system that not only increases the suction performance but also the dust filtration capacity. The design process focuses on minimizing the negative global impact through the following guidelines: helping customers to reduce their carbon footprint through the use of eco-friendly products with zero emission, that minimize the pollution of public spaces from CO_2, NOX, PM_{10}, noise emission, etc. The main initial goals of the electric sweeper development are zero emission, satisfying of customer's requirements and low cost for manufacturing the sweeper. The design methodology for the electric vacuum sweeper development, design and manufacturing will be presented in this paper. The design process includes: identification of market needs, planning, developing engineering specification, developing the concept and developing the product using CAD models, calculations, selection of materials, making technical drawings for prototype production and defining all necessary information for manufacturing. The overall design process for developing the electric vacuum sweeper will be presented through illustrative photos and the prototype will be presented.*

Keywords: *design process, electric vacuum sweeper, zero emission.*

6. INTRODUCTION

The electric street sweepers are machines which are mainly used for cleaning of urban area such as sidewalks and pedestrian area, streets and small roads in the city parks, etc. Due to the fast urbanisation in recent decades, air pollution in the metropolises and large cities has become a big problem for the inhabitants' health. The high level of pollution in the cities from CO_2, NOX, PM_{10}, noise emission, etc., in big range can be solved by using electric vehicles (EVs) or electric machines in the urban areas. There are many benefits of using EVs or over conventional petrol or diesel vehicles, such as [1, 2]: 1) cheaper to run, the cost of the electrical energy used in an EV is cheaper for 40% compared to the use of petrol or diesel in similar sized vehicles driving the same distance; the cost will be lower if the EV is charged by solar energy, 2) cheaper to maintain, the EVs has fewer moving parts than conventional petrol or diesel vehicles. Servicing of components in EVs is less frequent, relatively easy, and cheaper compared to petrol or diesel vehicles; 3) eco-friendly EV for the environment with less air pollution when EVs are charged from the electricity grid; zero air pollution if the EVs are charged from solar energy (photovoltaic system-PV) during the day or from electricity which is coming from renewable energy sources; 4) eco-friendly EV for our health because air pollution and noise pollution are practically zero, 5) better for electricity network, the EV charging is managed effectively, mainly outside from the peak electricity periods and that help us to utilise better the electricity network, avoid higher cost charging periods; 6) A quieter, more enjoyable driving experience, the EV drivers notice that an EV's quietness which creates a more comfortable, relaxing driving experience; 7) Fast, easy home or work charging of an EV is cost efficient, simple and fast; etc.

Electric mobility, according to the definition of the German government and the National Development Plan for Electric Mobility (NEP) comprises all street vehicles that are powered by an electric motor and primarily get their energy from the power grid – in other words: can be recharged externally [3]. Germany has started switching from energy obtained from fossil to renewable energy in 2011. By 2050, at least 80 percent of the electricity power supply and 60 percent of the total energy supply will originate from renewable energy sources. The all nuclear power plants are to be shut down by 2022 and then 40 to 45 percent of the electricity supply is to be stem from renewable energies by 2025 [4]. It will be suitable for development and applicability of EVs and electric mobility.

The electric street sweepers are part and parcel of electric mobility. There are three main categories of street sweepers: mechanical, regenerative, and vacuum filters. Each has its own set of advantages. In this paper will be presented the design process of the electric walk-behind sweeper GM 400ze (Green Machines – GM is company in Republic of North Macedonia which is among the oldest manufacturers of sweepers, dating back to 1965). The new developed model GM 400ze is a fully electric vacuum sweeper with zero-emission and zero-noise, the best walk-behind sweeper equipped with revolutionary air-recirculation system that not only increases the suction performance but also the dust filtration capacity.

7. BACKGROUND

The design and development of street sweeper machines and their brushes have evolved through time with legislation [5]. Peel et al. [6] have made an initial investigation into the dynamics of cutting brushes for sweeping and developed pseudo-static discretized model to investigate the deformations and forces which acting on the brushes during ideal operation of a horizontal brush on the flat plane. Budich et al. in the paper [7] developed vehicle simulation of a small electrical street sweeper for substitution analysis in the framework of the project EBALD in the Laboratory of Electric Mobility from the HTW Dresden. Based on collected field-data, collected during the project a simulation tool for substitution analysis was developed. By using this tool it's possible to say which conditions must be fulfilled (e.g. position of charging stations) to realize environmentally friendly and future-oriented cleaning concepts. This paper includes a structural approach on such a full vehicle's analysis. Considering the need for automated cleaning using less manpower, in the paper [8] Khan et al. developed solar operated street sweeping machine that can be used for cleaning small streets. The machines consist of solar panels and a battery unit which can be used to power the machine by an electric motor.

The design process focuses on minimizing the negative impact through reducing the ambient PM_{10} in the public spaces in big cities. The evaluation of street sweeping and washing to reduce ambient PM_{10} was considered from authors Chou et al in the paper [9, 10]. The paper [9, 10] presented an evaluation of street sweeping and washing by PM_{10} measurements and determination of silt load from active traffic streets. The reduction efficiency of ambient PM_{10} concentration of street sweeping and washing is determinated by measurements and it is up to 24%. The papers concluded that street sweeping and after that washing offer a measurable reduction in TSP (total suspended particles) emission potentials.

Yuan et al. [11] predicted and optimized the effects of reverse-blowing flow rate, pressure drop, and traveling speed on separation efficiency by using uniform design and multiple regression analysis methods. The presented results show that the dust collection performance firstly increased and then with increasing reverse-blowing flow rates are decreased. As pressure drop increased, there was an increase in total dust collection efficiency. Efficiency decreased with increasing traveling speed. The regression model showed that the proposed approach was able to predict the particle collection efficiency accurately.

Jin et al. [12] explored the influence law of various influencing factors on the flow field characteristics of the sweeper's dust suction port, and revealed its influence mechanism on the dust suction efficiency of the dust suction port. The presented results show that with increasing the width and outlet diameter will change the flow characteristics and the dust suction efficiency will be changed accordingly.

Xin et al. [13] presented the application of computational fluid dynamics (CFD) into the design of a road sweeper. The authors presented the use of CFD technology to analyze the flow field of the road sweeper airstream system while obtaining the characteristic parameters before it is manufactured.

Chen et al. [14] presented an electric vehicle's body frame structure design method approach to design an electric vehicle body structure based on battery arrangement. The main concept of the approach is the development of the parametric knowledge base to facilitate performance driven design of body structure in the concept design stage, including the battery designed by vehicle power performances and modular body frame structure.

In summary, the review of the research literature relevant to design process of a fully electric vacuum sweeper revealed that the previously published articles failed to address several important issues. The bigger problem is limited knowledge about the development of fully electric sweepers, because the electric road sweeper consists of a several power customers such as the main electric traction motor, the electric motor for vacuum suction system, electric motors for brushes, electric motor for water pump and other power customers, consists of a complex system for dust filtration with zero-emission and zero-noise. In this context, this paper aims to overcome the identified deficiencies and proposes a representation of a design process of a fully electric vacuum sweeper named as model GM 400ze.

8. DESIGN PROCESS METHODOLOGY

The design process of a fully electric vacuum sweeper is a complex process which consists of a several phases such as [15]: identification of market needs, project planning, product definition or definition of the product engineering specifications, conceptual design and developing the product using CAD models, calculations, selection of materials, making technical drawings for the prototype production and defining all necessary information for manufacturing. This project started as a collaboration between the company Green Machines DOO Veles and the Faculty of mechanical engineering in Skopje in order to improve and redesign their existing small vacuum sweeper GM400 with a diesel engine. In accordance with the market's needs the company Green Machines wanted to develop a fully electric vacuum sweeper with zero-emission of CO_2, NO_X, PM_{10}, noise, etc. The biggest problems with the old GM400 sweeper with a diesel engine are the large emission of PM_{10} particles and exhaust fumes. The sweeper's driver is exposed to a large amount of emissions and according to the new EU directives and market requirements the driver must be protected.

8.1. Identification of market needs, project planning and definition of engineering specifications

The project allotted from the company Green Machines was very clear and defined. The project description was defined with a set of customers' requirements, as follows: dimension of the new machine should be similar or smaller than current GM400 machine with diesel engine (see Fig. 1), design of the machine can be kept the same or very similar, performance of a new machine should be same or better than the GM400 machine with diesel engine (speed, suction capacity, capacity of waste collection, shredder function to be kept for compacting the waste), engine to be changed with several electric motors units (should be developed: traction axle with electric motor, a new electric motor and system for suction fan, a new electric motors for front brushes, electric motor with water pump as one unit, etc.), modification of chassis frame according requirements of the new electrical power units, develop/choose battery pack with integrated battery charger on machine, design the water system of machine, redesign of suction and collection system (extremely important dust control must be improved compared to current model with diesel engine), design of brake system which will be constructed according to new mass parameters, design of safety function, prototype building, test of prototype, etc. All these requirements which were allotted by the company come from market needs and their analysis.

Fig.1. Vacuum sweeper type GM400 - diesel engine [16]

Additionally, in order to understand the design problem translation of customers' requirements into a technical description of what needs to be designed, was made. The development of clear requirements is a key feature for an effective design process. The customers' requirements need to be translated to engineering specifications and the design team needs to understand the problem in order to write a good set of engineering specifications. In according to the market research table 1 with engineering specifications was made. The specifications were obtained from rival products. Engineering specifications from the main sweeper machine GM400 with diesel engine shown in the figure 1 are listed into table 1.
In table 1 are listed only a one small range of the engineering specifications for walk-behind sweepers: GM400 with diesel engine [16], Tenax Maxwind [17], TSM Italy 135 BT [18], NILFISK SW900 [19], DULEVO 52 [20] and PANGOLIN 300BT [21].

Table 1. Engineering specifications of rival products

Producer / Engineering specifications	GM 400 (diesel engine)	Tenax (Maxwind)	TSM Italy 135 BT	NILFISK SW900	DULEVO 52	PANGOLIN 300BT
Width [cm]	114	125	127	95	87	99
Length [cm]	251	186	200	139	132	205
Height [cm]	114,3	99	114	110	92	113
Mass [kg]	400	260	350	177	/	580
Autonomy [h]	/	6-8	8	8	/	8
Battery	/	AGM	AGM	AGM	AGM	AGM
Traction motor	Diesel	Elec	Elec	Elec	Elec	Elec
Dust control system	Yes	Yes	Yes	Yes	Yes	Yes
Sweeping system	Air	Central brush	Central brush	Central brush	Central brush	Central brush
Dust Spray Nozzles	Yes	Yes	Yes	Yes	Yes	Yes
Cleaning path [cm]	117	132	135	105	90	135
Sweeping speed [km/h]	5-8	8	6.5	4.5	4.5	4.5
Travel speed [km/h]	8.8	8	6.5	4.5	4.5	4.5
Waste hopper [L]	110 to 200	110 to 130	130	60	40	220

In summary, after a first project description allotted from the company Green Machines, market research and a lot of held meetings between the engineering teams from company Green Machines and the Faculty of mechanical engineering in Skopje, the engineering specifications of a new fully electric vacuum sweeper GM400ze were defined. The approximately engineering specifications of GM400ze machine are: width 110 [cm], length 200 [cm], height 110 [cm], mass 450 [kg], autonomy 8 [h], type of battery li-ion, all motors will be electric, sweeping system to be with two front brushes, suction fan with shredder function, waste collection system with waste trash bag from 200 L, sweeping speed in range of 5-8 [km/h], travel speed maximum up to 10 [km/h], maximum slope 25%, dust spray nozzles, water tank with 70 L, dust control system, wander hose with length from 2 [m], etc.
A project plan is a document which includes the tasks that need to be realized during the design process and keep the project under control. The design team and management with help of the project plan will know how the project is progressing during realization. The project plan consists of the tasks, the personal requirements, the time requirements, the schedule of tasks, cost estimates, etc. The best way to make a good project plan is to use a Gantt chart. On the chart each task is plotted against a time scale, the personal requirement and schedule of design reviews is shown.

The segment of project planning for project development of fully electrical vacuum sweeper GM400ze is shown onthe figure 2. Duration time for the project is 7 months from market research to the building of prototype, testing and finally preparation of technical documentation.

Project No1:Development of electrical version of the GM400 series machine

	Duration time (2020/2021)						
	October	November	December	January	February	March	April
Tasks:							
0. Making concept of a new machine, identifying which components will be retained and which components will be changed. Definition of the limit dimensions / volume for new components.							
1. Change current diesel engine with several electric motor units	Engineers: FME						
1.1. Develop new or adopt current transmission-differential axle which will be powered by electric motor and will provide traction of the machine	Engineers: FME						
1.2. Develop/choose new electric motor for suction fan	Engineers: FME						
1.3. Develop/choose new electric motors for front brushes	Engineers: FME						
2. Modification of construction/chassis frame according requirements of the new electrical power units	Engineers: FME						
3. Develop/choose battery pack with integrated battery charger on machine ➢ Autonomy of using with all consumptions turned ON, more than 6 hours ➢ Possibility to connect external consumer with available plug	Engineers: GM						
4. Design (update) the water system of machine	Engineers: FME						
5. Design (update) the lights and voice signalization of machine	Engineers: FME						
6. Redesign of suction and collection system	Engineers: FME						
6.1. Reduce the dust during machine work	Engineers: FME						
6.2. Redesign if possible the system for changing of garbage bags	Engineers: FME						
.....							
.....							
13. Preparing technical documentation							
13.1. 3D model	Engineers: FME						
13.2. Technical drawings 2D for production	Engineers: FME						
13.3. Process notes for assembly	Engineers: FME						
13.4. Datasheets for components	Engineers: FME						
13.5. Owner's manual	Engineers: FME						
13.6. Service manual	Engineers: FME						
13.7. Spare parts catalog	Engineers: FME						

Legend: FME-Faculty of mechanical engineering, GM-Green Machines

Fig.2. Project planning with Gantt chart

8.2. Conceptual design and concept evaluation

A concept is an idea that is sufficiently developed to evaluate the physical principles that govern its behavior [15]. The electric vacuum sweeper machine GM400ze is divided onto subsystems such as: traction unit, suction unit, seat, cover plastic, water spray system, etc. Traction unit consists: transaxle electric motor, hydraulic drum brakes, complete waterproof design, differential, differential lock device and double raw ball bearing. According to [22] calculations for obtaining of traction parameters is obtained: power of traction motor is 3 [kW], capacity of Li-Ion battery is 10 [kWh] that can last 8 hours for full work-shift autonomy, travel maximum speed up to 10 [km/h], maximum slope 25%, etc. The traction calculation is general and concept for traction unit is a very clearly and simple. The electric transaxle is shown in the figure 3.

The suction unit is a complex system which consists of a vacuum unit with centrifugal fan with shredder function, flexible hose, channels, filter bag, plastic nylon bag for garbage, etc. The main aim in this paper is zero-emission or near to zero-emission of PM_{10} particles. The conceptual design focuses on minimizing of PM_{10} emission around the sweeper. Four different concepts which are shown in the figure 4 to figure 7 were generated.

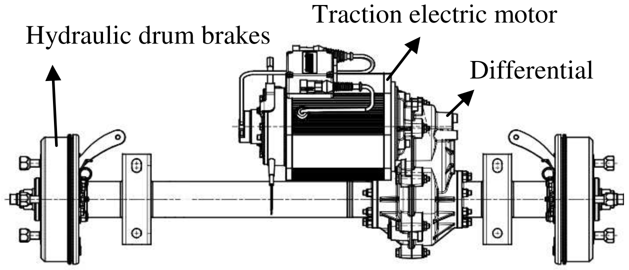


Fig.3. Electric transaxle

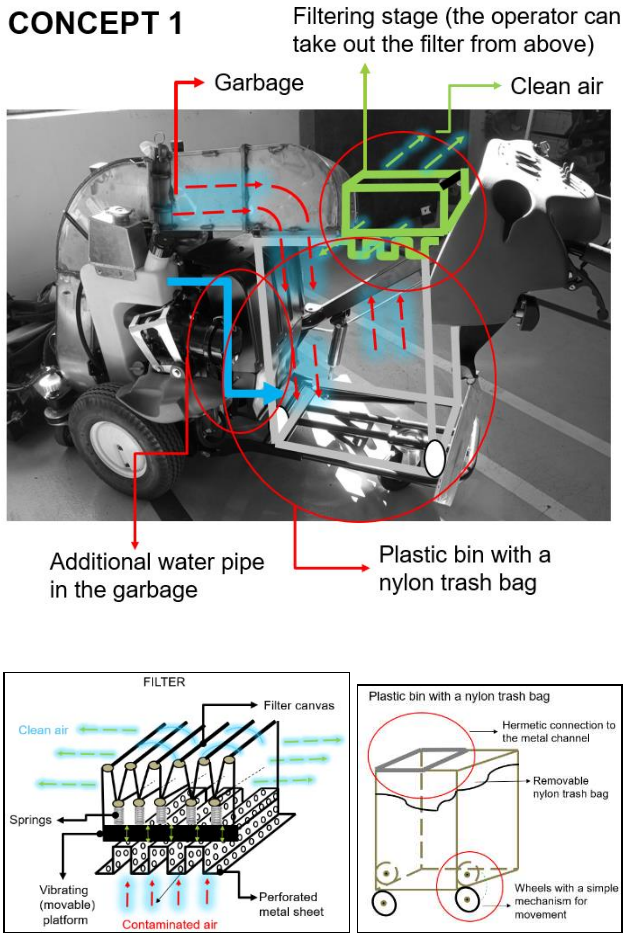


Fig.4. Concept design 1

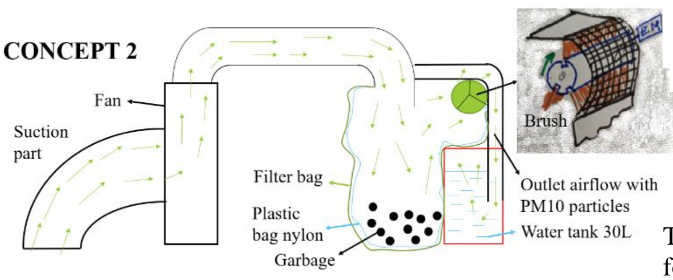


Fig.5. Concept design 2

The mechanical solution with filter canvas and springs for removing the particles from the canvas was a first concept design which is shown in figure 4.

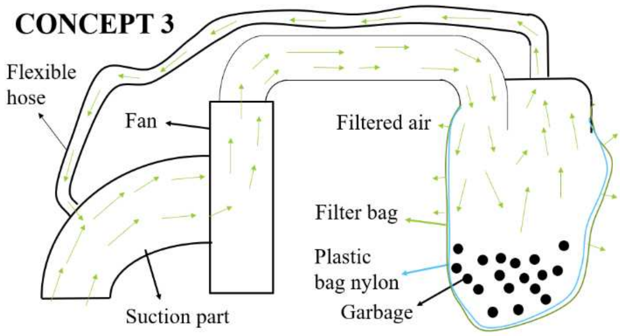


Fig.6. Concept design 3

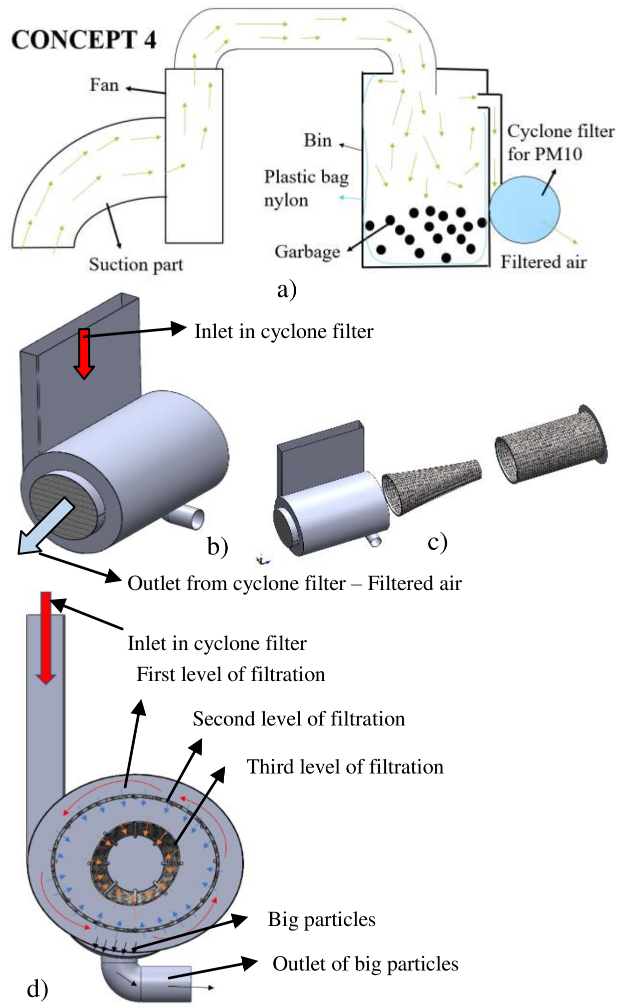


Fig.7. Concept design 4: a) concept, b) cyclone filter for PM10, c) exploded view of cyclone filter and d) section view of cyclone filter

The concept design 1 consists of a plastic bin with wheels for easy garbage removal and inside the plastic bin there is a nylon trash bag.The air flow with a lot of PM_{10} participles passes across a filter canvas and filtered air comes out from the machine. The filter canvas is connected with springs and an actuator which vibrate and remove particles form the filter canvas. The concept design 2 which is shown in figure 5 consists of filter bag, nylon bag for garbage, system for removal of bigger parts from garbage with rotating brush and filtering system

with water for filtering PM_{10} particles. The air flow with a lot of PM_{10} participles passes across water and filtered air comes out from the machine. The filter bag also allows purification of bigger part form contaminated air with PM_{10} particles. The other part from air flow with PM_{10} participles pass across filtering system with water. The concept design 3 shown in figure 6 consists filter bag, nylon bag for garbage and flexible hose for air-recirculation. The air-recirculation system allows air flow with a PM_{10} particles to recirculate and stay into the sweeper in order to reduce emission of PM_{10} particles. The concept design 4 shown in figure 7 consists trash bin, nylon bag for garbage and cyclone filter for removing of PM_{10} particles. The cyclone filter allows purification of contaminated air with PM_{10} particles. Air flow with PM_{10} participles passes across a cyclone filter and is filtered. The cyclone filter has three levels of filtration. The first level of filtration under centrifugal force separates the bigger particles from the air. The big particles go to the outlet. The second level of filtration is through a cylindrically shaped filter canvas. The third level of filtration is also through a conically shaped filter canvas.
All of the concept designs contain a suction system as shown in figure 8 with an inlet flexible hose, a centrifugal fan with shredder function and a metal channel. The outlet of the suction system goes to the garbage bag and filtration system. These parts are retained from the old sweeper with a diesel engine shown in figure 1. The arrows show directions of air and garbage traveling through the sweeper.

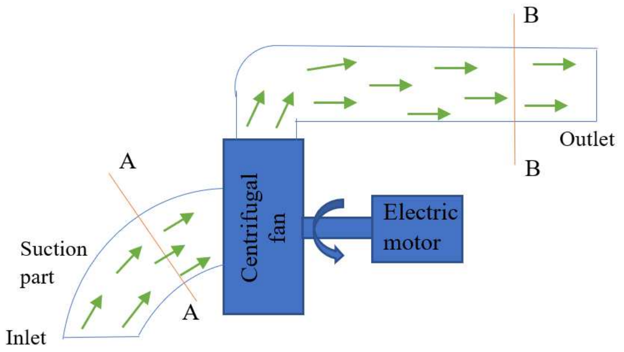


Fig.8. Schematic representation of suction system

The values of air velocities and pressures in the sections A-A and B-B in the suction system shown in figure 8 are experimentally determined according to the old sweeper with a diesel engine. The values were used for determination of electric motor parameters.
The motor power *P* [W] is calculated by the below equation:

$$P = \frac{\Delta P \cdot Q}{\eta} \qquad (1)$$

where ΔP [W] represents the pressure drop, Q [m^3/h] represents air flow and η represents efficiency of centrifugal fan. The values of pressure drop ΔP and air flow Q are calculated according to experimentally obtained values of velocities and pressures in section A-A and B-B, shown in figure 8. The efficiency of the centrifugal fan is in range $\eta = 0{,}5\text{-}0{,}6$.

The motor torque T [Nm] is calculated by the equation below:

$$T = \frac{P}{\omega} = \frac{30 \cdot P}{\pi \cdot n} \qquad (2)$$

where *P* [W] represents motor power and *n* [rpm] represents rotation per minutes of a centrifugal fan. The number of rotations was experimentally determined according to the old sweeper with diesel engine.
According to previous calculations, the electric motor was chosen with the following parameters: fan motor power from 5,5 [kW] and vacuum fan speed up to 2700 [rpm].
The proposed concepts were made and tested in order to experimentally proof their functionality. In figure 9 prototypes of the concepts are shown. The concept design 3, shown schematically in figure 6 and shown as prototype in figure 9 c), gave the best results with a very small emission of PM_{10} particles practically zero-emission.

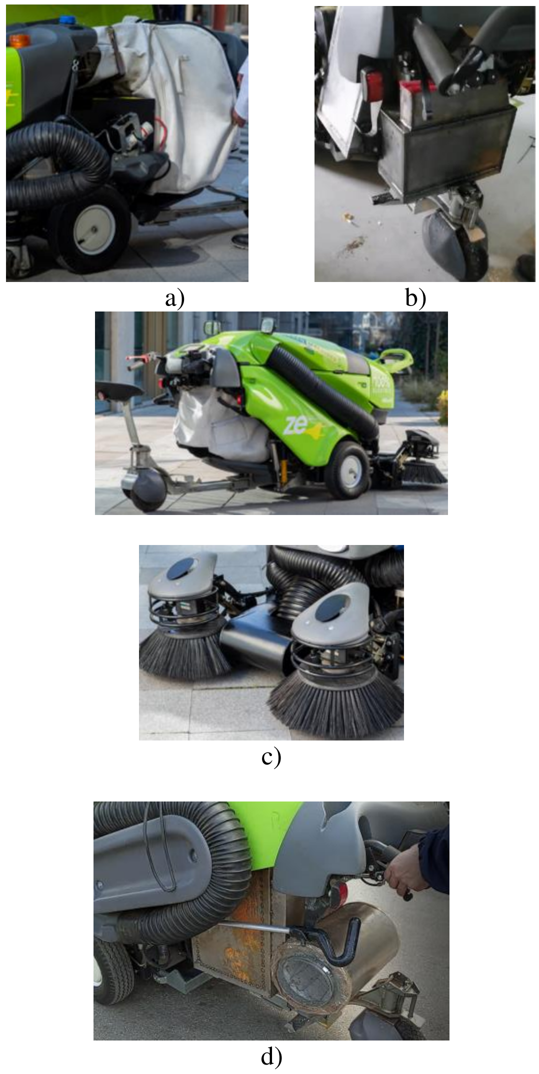


Fig.9. Prototypes of concept: a) design 1, b) design 2, c) design 3 and d) design 4

In order to proof the efficiency a new concept solution of the sweeper with air recirculation system for reducing of PM_{10} particles and old sweeper with a diesel engine were tested together in same conditions in according to standards EN 481 [23], EN 482+A1 [24] and CEN/TR 15230 [25]. According to the standards measurement equipment was used: personal sampling pump (fig. 10. b)), analytical weighing device (fig. 10. c)) and conical inhalable sampler (fig. 10. d) and e)). In figure 10 is shown the measurement equipment for workplace atmospheres and illustration of equipment installation (fig.10 a). The old sweeper with a diesel engine exists on the market more than 30 years and has international approval according to standards EN 481 [23], EN 482+A1 [24] and CEN/TR 15230 [25]. The value for respirable dust for the old sweeper is under 5.0 mg/m^3.

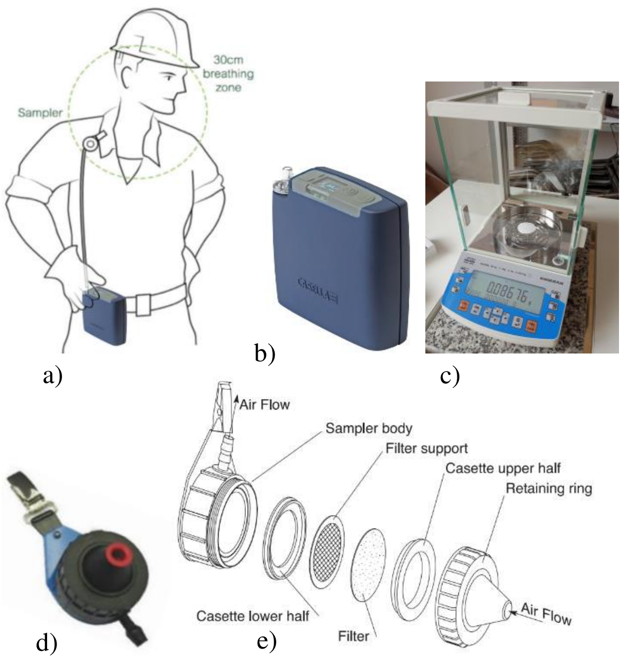


Fig.10. Measurement equipment: a) installation, b) personal sampling pump, c) analytical weighing device, d) conical inhalable sampler and e) exploded view of conical inhalable sampler [26]

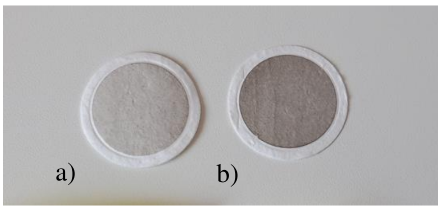


Fig.11. Filters after measurement: a) novel design with air-recirculation system and b) old sweeper with diesel engine

In figure 11 are shown filters after measurement for novel design with air-recirculation system and old sweeper with diesel engine. The obtained results show that the novel design with an air-recirculation system is three times better than the old sweeper with diesel engine. The novel design collected 34 [kg] garbage (fig. 12 a) and the old sweeper with a diesel engine collected 17 [kg] garbage (fig. 12 b) in the same working time and same conditions.

In summary, the novel design of revolutionary air-recirculation system is better than the old. The new design not only increases the suction performance but the dust filtration capacity as well.

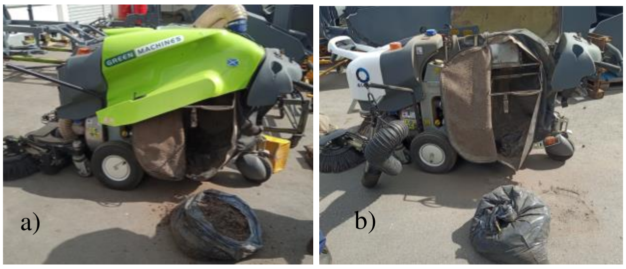


Fig.12. Sweepers: a) novel design with air-recirculation system and b) old sweeper with diesel engine

8.3. Product development

The product design phase is focused on refining the concept into a high - quality product. The product's design is evaluated for its performance, robustness, quality and cost. After all the important aspects were considered, such as performance, robustness, quality and cost, a novel design of a fully electric vacuum sweeper was created. The electric vacuum sweeper GM400ze was modelled with the application of the SolidWorks software, using modules: part, assembly, sheet metal, surface modelling, etc. In the figure 13 the 3D assembly model in SolidWorks of the vacuum sweeper is shown. The assembly model consists of more than 1500 parts and more than 35 subassemblies.

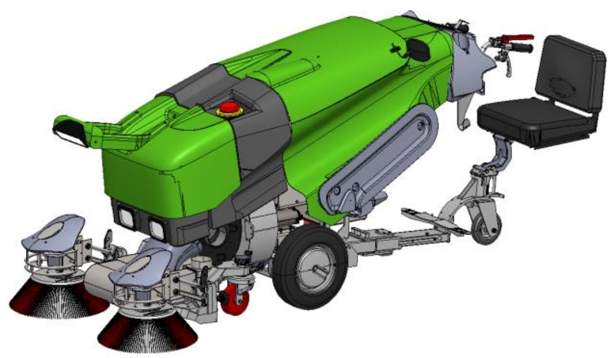


Fig.13. 3D assembly model in SolidWorks of a novel design of electric vacuum sweeper

The product design in SolidWorks was an iterative process and when finished the next step was creating technical documentation and dxf files for production. The technical documentation includes technical drawings for production, process notes for assembly, datasheets for component (BOM-Bill of materials), owner's manual, service manual, spare parts catalog, etc. Preparation of technical documentation is a very difficult and travail work for engineers. Manufacturing of metal components is carried out using laser cutting machines for sheet metal and pipes, bending, milling, etc. Electric and electronic components were ordered from other manufacturers using catalogues.

Additionally, more features were created, such as working beacon, touchscreen tablet, flexible suction hose for hard to reach areas, expandable chariot system that allows more comfort, etc. In figure 14 options of a new sweeper are shown. Significant additional features are touchscreen tablet (fig. 14 b) and air-recirculation system (fig. 14 c). The dimensions of the electric sweeper (2997 x 1140 x 1243 [mm]) are shown in figure 14 d) together with the sweeper's weight 500 [kg].
The electric sweeper was tested in real conditions and showed that it has excellent slope performance and overcame a slope of 25%. The maximum travel speed is 12 [km/h]. The sweeper has excellent suction performance when centrifugal fan has speed in the range between 1400-1800 [rpm]. The battery consumption is in range between 1400-1800 [rpm] when fan speed is in range between 15-18% per hour, the battery consumption in travel speed is about 7%, the battery consumption can satisfy a full 8 - hour work-shift autonomy with 10 [kWh] lithium-ion battery as standard. The electric sweeper has nearly zero-emission of PM_{10} particles which is a result of the revolutionary air-recirculation system which improves the suction and dust filtration and decreases particle exhaust three times.
Operational time and battery consumption in full work-shift are listed in table 2. The travel mod is the operation when sweeper goes from place of sweeper storage to working place and opposite. In travel mod only the electric motor from transaxle, display and electronics work. The working mod is the operation when all consumers work, such as the electric motor from transaxle, suction system, front brushes, display, electronics, etc. Operational time in working mod is 5 hours and in this mod the battery consumption is the biggest. The rest of the time the machine is switched off. Table 2 is obtained experimentally and it confirms that the machine can satisfy 8 hours with full work-shift autonomy with a battery capacity of 10 [kWh].

Table 2. Operational time and battery consumption

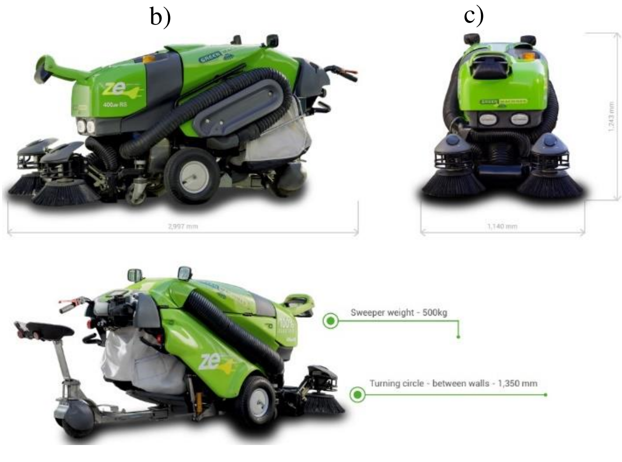
Operations	Operational time [hours]	Battery consumption [%]
Travel mod	1 (1 x 7=7%)	7%
Working mod	5 (5 x 17=75%)	85%
Breakfast or lunch break	0,5	0%
Maintenance of machine	0,5	0%
Throwing garbage	0,25	0%
Cleaning and washing of machine	0,5	0%
Trash bag placement	0,25	0%
Total	8	92%

9. CONCLUSION

This paper presented the design process of a fully electric vacuum sweeper with zero-emission and zero-noise, the best walk-behind sweeper equipped with a revolutionary air-recirculation system that not only increases the suction performance but also the dust filtration capacity. All stages of the design process are described. Such stages are: identification of market needs, project planning, definition of the product's engineering specifications, conceptual design and evaluation, product development using CAD software, testing, etc.
The project was a collaboration between the company Green Machines DOO Veles and the Faculty of Mechanical Engineering in Skopje in order to improve and redesign their existing small vacuum sweeper GM400 with a diesel engine into fully electric vacuum sweeper GM400ze.

a)

b) c)



d)

Fig.14. The sweeper features: a) additional features, b) touchscreen tablet, c) air-recirculation system and d) dimensions and sweeper weight [16]

The new sweeper GM400ze was tested in real conditions and showed excellent performance in the main aim of the project toward reducing PM_{10} particles in order to satisfy the European standards for workplace atmospheres and protect the operator from PM_{10} particles. The GM400ze performances are: fully electric sweeper, 8 hours one work-shift autonomy, use of a 10 [kWh] lithium-ion battery, maximum slope of 25%, the maximum travel speed is 12 [km/h], excellent suction performance, quiet operation, easy maneuver, digital control display, ergonomic control handles, easy to use wander hose, simple daily maintenance, etc. The plastic cover grants swift access to the debris grinder and trash compacting storage compartment so maintenance and cleaning can be performed with ease and high efficiency, saving a lot of time and energy.

The presented electrical sweeper GM400ze can be further upgraded in the future with additional modules to obtain an improved version of a sweeper such as online tracking for aspect of maintenance, easy service, optimizing, etc.

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REFERENCES

[1] https://www.ergon.com.au/network/smarter-energy/electric-vehicles/benefits-of-electric-vehicles - Ergon Energy2022, Accessed on: 2022-04-15

[2] https://www.goultralow.com/ev-owners/benefits/- Go Ultra Low, Accessed on: 2022-04-15

[3] https://www.erneuerbar-mobil.de/en/node/970 - German government and the National Development Plan for Electric Mobility (NEP), Accessed on: 2022-04-15

[4] https://www.deutschland.de/en/topic/politics/germany-europe/what-you-should-know-about-the-energy-transition - Carbon neutral website, Accessed on: 2022-04-15

[5] Pratt, T., and Yule, J.: *A Brief History of the Road Sweeper*, J & G Plant Ltd,1997

[6] Peel, G. M., and Parker, G. A.: Initial Investigations into the Dynamics of Cutting Brushes for Sweeping. ASME. *J. Dyn. Sys., Meas., Control*. Vol. 124, No. 4, pp. 675–681, December 16, 2002, https://doi.org/10.1115/1.1515333

[7] Budich, R., Hübner, M.: Vehicle simulation of an electric street sweeper for substitution analysis. In: Bargende, M., Reuss, HC., Wiedemann, J. (eds) *16. Internationales Stuttgarter Symposium. Proceedings. Springer, Wiesbaden*, 28 April 2016, Stuttgart, pp 673–690, https://doi.org/10.1007/978-3-658-13255-2_50

[8] Khan, J., Bhapkar, U., Bhat, J., et al.: Design and development of smart solar powered street sweeping machine, *Materials Today: Proceedings*, Elsevier, Vol. 46, Part 17, 2021, pp. 8663-8667, https://doi.org/10.1016/j.matpr.2021.03.662

[9] Chou, C.M., Chang, Y.M., Lin, W.Y., Tseng, C.H., Chen, L.: Evaluation of street sweeping and washing to reduce ambient PM10. *Int. J. Environment and Pollution*, Vol. 31, No. 3-4, 2008, 10.1504/IJEP.2007.016507

[10] Chang, Y.M., Chou, C.M., Su, K.T., Tseng, C.H.: Effectiveness of street sweeping and washing for controlling ambient TSP. *Atmospheric Environment*, Vol. 39, No. 10, pp. 1891-1902, 2005, https://doi.org/10.1016/j.atmosenv.2004.12.010

[11] Xi, Y., Dai, Y., Zhang, X.I., Zhang, X.: Prediction of Particle-Collection Efficiency for Vacuum-Blowing Cleaning System Based on Operational Conditions. *Processes*, Vol. 8, No. 7, pp. 809, 2020, https://doi.org/10.3390/pr8070809

[12] Jin, Y., Jiabao, P., Hejin, A., Lujun, Z. Relationship between flow field characteristics and dust collection efficiency of sweeper suction port. *The Journal of Engineering*, Wiley, Vol. 2022, No. 4, pp. 389-400, 2022, DOI: 10.1049/tje2.12122

[13] Xin, Y., Li, H., Wu, J.: Applications of CFD technique in the flow field analysis of road sweeper. *Applied Mechanics and Materials*, Trans Tech Publications, SwitzerlandVol. 733, pp. 583-586, 2015, doi:10.4028/www.scientific.net/AMM.733.583

[14] Chen, X., Wang, J., Zhao, K., Yang, L.: Electric vehicles body frame structure design method: An approach to design electric vehicle body structure based on battery arrangement. *Proceedings of the Institution of Mechanical Engineers*, *Part D: Journal of Automobile Engineering*, October 2021. doi:10.1177/09544070211052957

[15] Ulman, D. G.: *The Mechanical Design Process, Fourth edition*, McGraw-Hill Series in Mechanical Engineering, Boston, ISBN 978–0–07–297574–1, 2010

[16] https://greenmachines.com/400-2/ - Green Machines, sweepers, Accessed on: 2022-04-21

[17] https://www.tenaxinternational.com/en/prodotto/electric-sidewalk-sweeper-maxwind/ - Tenax, sweepers, Accessed on: 2022-04-21

[18] https://www.tsmitaly.com/en/professional-cleaning-machines/sidewalk-sweepers/itala-135-bt/ - TSM Italy, sweepers, Accessed on: 2022-04-21

[19] https://www.nilfisk.com/global/products/floor-cleaning/sweepers/walk-behind-sweepers/sweeper-sw900-84b/p_9084110010/ - Nilfisk, sweepers, Accessed on: 2022-04-21

[20] https://www.dulevo.com/products/sweepers/dulevo-52/ - Dulevo, sweepers, Accessed on: 2022-04-21

[21] https://ertugproje.com/en/product/electrical-vacuum-sweeper-for-pavement-and-square-pangolin-300-bt-p-374, ERTUĞ PROJE, sweepers, Accessed on: 2022-04-21

[22] Danev, D., Kjosevski, M.: *Instructions for making traction calculation of motor vehicles*, Faculty of Mechanical Engineering - Skopje, Skopje,1999

[23] EN 481 (1993), Workplace atmospheres – Size fraction definitions for measurement of airborne particles
[24] EN 482 (2012) + A1 (2015), Workplace exposure – General requirements for the performance of procedures for the measurements of chemical agents
[25] CEN/TR 15230 (2005), Workplace atmospheres – Guidance for sampling of inhalable, thoracic and respirable aerosol fractions
[26] Company Casella: *Air sampling handbook*, www.casellasolutions.com, Accessed on: 2022-04-28

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INNOVATIVE DESIGN SOLUTIONS OF GEAR TRANSMISSIONS FOR INDUSTRY 4.0

Milan RACKOV

Abstract: *Gear transmissions are relatively simple mechanisms whose quality, price, delivery time and design appearance are almost equal. This is the common reason why it is very difficult for all gear manufacturers to ensure the successful placement of their products on the market. However, regardless of their simplicity, gear transmissions may have different design and technical solutions, and due to different limitations of individual components, the calculation of load capacity and other technical characteristics can be quite complicated. In accordance with the basic settings of Industry 4.0, smart transmissions are being developed that will be able to provide a certain advantage over the competition and thus, for sure, ensure the successful business of these innovative companies. This paper describes the basic principles of construction using new technologies, primarily using the Internet of Things and digital twins. The paper includes an analysis of approaches to the creation of Digital Twins. Describe why Industry 4.0 is so different and specific, define what is Cyber-physical systems and the Internet of Things, and what is predictive monitoring with using different sensors.*

Keywords: *Innovative design, Gear transmissions, Digital twin*

1. INTRODUCTION

Due to the very strong competition, all gear manufacturers are trying to create some advantage over the competition in order to improve the placement of their products on the market. Many manufacturers try to attract customers by short delivery times. Other manufacturers try to achieve this with high quality, although there are also manufacturers who try to obtain customers with low prices (which is achieved either with cheaper labour, a more favourable conceptual solution, or slightly lower quality of their gearboxes). Of course, some manufacturers obtain customers with a high-quality level of gear transmissions and also with a more attractive appearance of their gearboxes. [1]

Gears, depending on their application, have different dimensions, design, technical characteristics, as well as different damages, failures and limited conditions under which they are determined. They are certainly among the most complicated mechanisms for calculation, design and construction and have a very important and general significance in modern mechanical engineering. [2] Modern solutions of universal helical gearboxes are characterized, first of all, by large torque capacity and high values of gear ratio in the frame of relatively small overall dimensions of the gear unit. [1]

The rapid development of information and communication technologies (ICT) has led to the development of the fourth industrial revolution, i.e. Industry 4.0, which is based on the use of information and communication technologies (ICT) and their communication using the Internet. This brings additional new components that are necessary for modern power transmissions, and without which it is impossible today to perform modern design, production, supervision and maintenance.

2. IMPLEMENTATION OF INDUSTRY 4.0 AS A MODERN DEVELOPMENT OF GEAR DRIVES

Industry 4.0 offers huge potential for improvement and success not only in the field of gear drives production but mostly for product innovation. Efficient engineering of the new generation of smart products and services is appeared, as well as new business models that are used in their marketing. In order to be able to successfully use this potential, manufacturers are facing a great process of transformation, i.e. cardinal changes where they have to overcome many challenges.

The focus of these changes is mostly related to process models, methods, IT tools and information models in the development of smart products and services. The development of products and services is the most important phase of engineering since in this phase lies the greatest innovation potential and the characteristics of future products are determined here. [3]

The essential goal of Industry 4.0 is to make manufacturing – and related industries such as logistics –

faster, more efficient and more customer-centric, while at the same time going beyond automation and optimization and detecting new business opportunities and models. In that way, personalization and customization of gear drive manufacturing will be established.
The fourth industrial revolution arose in the correlation between the existing traditional industry and innovations in the field of the Internet, i.e. in the field of information and communication technologies (ICT).
Innovations based on ICT can be divided into five categories (Fig.1):

- Internet (Internet of Things, Internet service, ...);
- Hardware (smart devices, cloud computing, augmented reality, ...);
- Software (service-oriented architecture, semantic and Big-Data technologies, ...);
- Communication (5G, WiFi, ...);

Built-in microsystems (microprocessors, microsensors, microactuators, ...). [3]

Fig.1. Industry 4.0 – the digital transformation

Trends in the development of modern technical facilities and their production largely refer to the ideology of Industry 4.0, in which a key role is played by the development of the sensor base and intellectualization of machines and materials [4], the Internet of things (IoT) and the creation of digital twins of items.
Industry 4.0 is characterized by much better automation, the bridging of the physical and digital world through cyber-physical systems, enabled by Industrial IoT. A central industrial control system is shifted to one where smart products define the production steps, there are closed-loop data models and control systems and personalization and customization of products are applied.
The basic structure of industrial products (BMS), in this case, gear transmission, consists of mechanical components (gears, shafts, bearings, etc.) (Fig.2). In further evolutionary development, this structure was supplemented by electronic components and software, thus creating mechatronic products (MP). As a result of the development of miniature microcomputers and further software development, mechatronic products were equipped with artificial intelligence, so intelligent mechatronic products (IMP) appeared. In the next evolutionary step, products are enhanced by the ability to communicate with other products and the Internet. These products are called “Cyber-Physical Systems” (CPS). [3]
Cyber-physical systems form the basis of Industry 4.0 (e.g., smart machines). They use modern control systems, have embedded software systems and dispose of an Internet address to connect and be addressed via the Internet of Things (IoT). [6]
The cyber-physical systems are the basis and enable new capabilities in areas such as product design, prototyping and development, remote control, services and diagnosis, condition monitoring, proactive and predictive maintenance, track and trace, structural health and systems health monitoring, planning, innovation capability, agility, real-time applications and more. [6]
Looking at Industry 4.0 as the next new stage in the organization and control of the value chain across the lifecycle of products, this ongoing improvement in which CPS fits started from mechanical systems and moved to mechatronics (where controllers, sensors and actuators are used) and adaptronics, and is now entering this stage of the rise of cyber-physical systems.
Cyber-physical systems essentially enable us to make industrial systems capable to communicate and network them, which then adds to existing manufacturing possibilities.
They result to new possibilities in areas such as structural health monitoring, track and trace, remote diagnosis, remote services, remote control, condition monitoring, systems health monitoring and so forth. [6]
Characteristics of cyber-physical systems:

- CPS represents an evolution in manufacturing, mechanics and engineering because they provide digital and physical bridging of system components, which is possibly thanks to Internet technology, and the bridging/convergence of Information Technology and Operational Technology;
- CPS can communicate since they have intelligent control systems, embedded software and communication capabilities as they can be connected in a network of cyber-physical systems;
- CPS can be uniquely identified because they dispose of an IP (Internet Protocol) address which means that they use Internet technology and are part of an Internet of Everything in which they can be uniquely addressed (each system has an identifier);
- CPS must have controllers, sensors and actuators (but this was already the case in previous stages before cyber-physical systems in mechatronics and adaptronics);
- CPS are the basic building blocks of Industry 4.0 and the enablers of additional capabilities in manufacturing such as track and trace and remote control;

The capabilities which are possibly thanks to cyber-physical systems enable smart factories, smart logistics (Logistics 4.0) and other smart areas of applications.

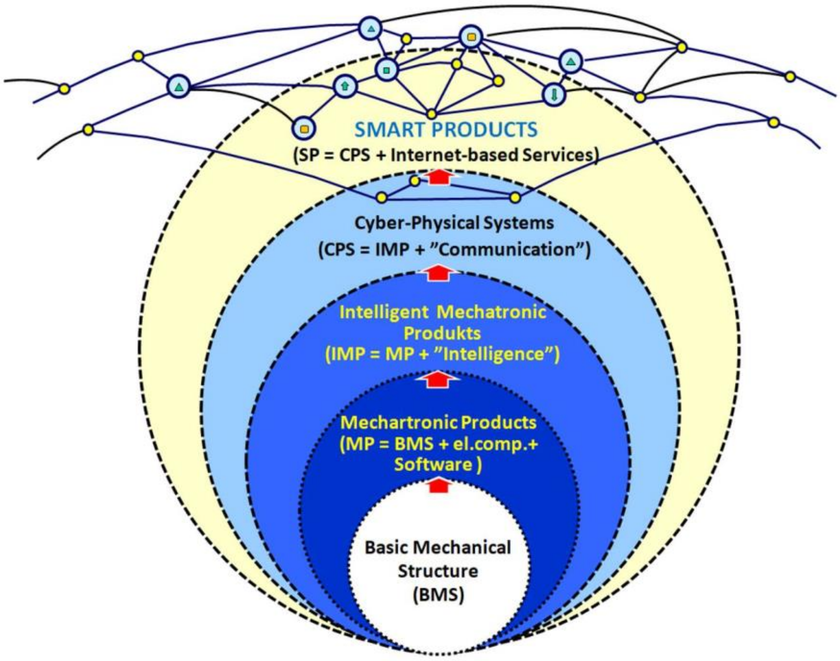

Fig.2. Evolution of stages from machine products (BMS) to smart products (SP) [5]

Industry 4.0 offers multiple benefits for the production of gear transmissions. Central requirements from gear drive production are increased productivity, flexibility, quality and speed production (Fig.3). One of the first goals of Industry 4.0 is productivity through optimization and automation. In other words: saving costs, increasing profitability, reducing waste, automating to prevent errors and delays, speeding up production to work more in real-time and in the function of the overall value chain, where speed is crucial for everyone, digitizing paper-based flows, being able to intervene faster in case of production issues.

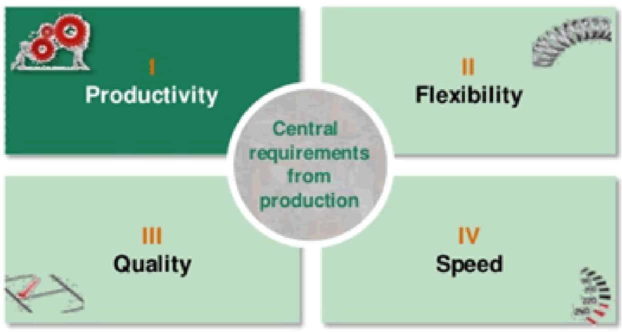

Fig.3. Industry 4.0 offers multiple benefits for production

Productivity increasing of gear drives can be obtained by using a higher level of automation that reduces production time and enables better asset utilization and inventory management. The flexibility of gearbox manufacturing can be realized through machines and robots that can execute the production steps for a large number of products. Sensors and actuators that monitor the current production in real-time and quickly intervene in case of errors increase gear transmission quality. Production speed is increased by using consistent data and, e.g. new simulation opportunities.

There is also improvement of manufacturing conditions. For example, occupational safety is improved through increased automation. Ergonomically adapted workstations offer better working conditions. Increased collaboration in the product network is the result of consistent data availability. Environment is better protected by using optimized use of resources (e.g., more energy-efficient operation of machinery). Inovative capability is increased through new technological possibilities in manufacturing.

New generations of automated sensors connected to the Internet and supported by developed hardware and software tools enable the creation of fully digitalized factories. Industry 4.0 has already been introduced in many countries, thus ensuring the survival of the industry and its competitive development in modern conditions. Modern digital technologies such as the Internet of Things (IoT), robotics, cloud computing, cyber-physical systems and scalable big data analytics are key to implementing the Industry 4.0 concept. Industry 4.0 implies complete digitalization of all production processes and application of the mentioned digital technologies when creating an idea about a product, product engineering, production organization, production realization, process control and provision of industrial services. [4]

3. INTERNET OF THINGS AND INDUSTRY 4.0 AT GEAR DRIVES DEVELOPMENT

Trends in the development of modern technical facilities and their production largely refer to the ideology of Industry 4.0, in which a key role is played by the development of the sensor base and intellectualization of machines and materials, the Internet of things (IoT) and the creation of digital twins of items.

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The Internet of Things (IoT) is a new type of communication between intelligent devices. Practically, a parallel internet is being created in which things communicate with each other, exchange information, manage each other, react and influence the environment in which they find themselves, without the influence of people. [3]

The presence of an IP address by definition means that cyber-physical systems, as objects, are connected to the Internet (of Things). An IP address also means that the cyber-physical system can be uniquely identified within the network. This is a key characteristic of the Internet of Things as well.

Cyber-physical systems are also equipped with sensors, actuators and all the other elements which are part of the Internet of Things. Cyber-physical systems, just like the Internet of Things need connectivity.

The Internet of Things consists of objects with embedded or attached technologies that enable them to sense data, collect them and send them for a specific purpose. Depending on the object and goal this could be capturing data regarding movement, location, presence of gasses, temperature, 'health' conditions of devices, the list is endless. [7]

IoT devices can also receive data and instructions, again depending on the 'use case'. All this applies to cyber-physical systems as well, which are essentially connected objects. There are more similar characteristics, but there are already many common things.

The Internet of Things focuses on looking for all the influences that surround a machine system to provide the right hardware and software to give this system a market advantage. In Industry 4.0, technology is required to be more scalable and flexible enough to respond well to changes in the supply chain as well as the entire product line. The main difference that makes both IoT and Industry 4.0 technologies key components of advanced industry transformation is connectivity. IoT seeks to connect everything to the Internet, and Industry 4.0 describes the idea of connecting sensors, actuators, control units, logistics services, other planning systems, and so on. [4] Because data-intensive industries require secure and reliable technology that is capable of storing and processing data in the cloud for better availability.

The advanced companies that introduced Industry 4.0 strive to manage their business remotely to achieve better results in an economical price structure. IoT allows remote monitoring of each device in real-time. It also keeps data secure and requires less manual work through all of these operations.

Machine systems are required to have efficient tools or systems that help manage big data and use it to infer outcomes based on different situations. IoT technology includes sensors and advanced connections of all components that are controlled and monitored. This way of connecting enables quick answers and better decision making at the right time.

The Internet of Things promotes effective machine system management strategies and improves their performance thanks to a constant control system. This helps to reduce their workload through manual handling of each task and to automate the entire industrial processing. Thus, it leads to relatively simpler maintenance of the device and simplifies the decision-making process.

3.1. Major Differentiators of IoT and Industrial IoT

The term internet of things (IoT) is often used these days. This technology is nothing but smart devices that are having good connectivity and can communicate with each other seamlessly. The number of IoT devices is growing exponentially with each passing day.

Table 1. Differences between IoT and Industrial IoT [7]

Points of distinction	IoT	Industrial IoT
Security	Not critical	Is a crucial element
Scalability	Limited data processing	Support large scale network
Development focus	To improve consumer convenience	To make industrial operations efficient and effective
Interoperability	Not much integration required	Integration with legacy Operational Technologies
Precision	Can be close to accurate	Should be accurate

An almost identical term used is Industrial IoT (IIoT). Although both of these terms sound almost the same, because they are both based on the same technology and depend on the interconnection of devices, there are significant differences in these two concepts. [7] IoT is usually used by consumers, and as the name suggests, industrial IoT is for industry, such as manufacturing, transportation, etc. Table 1 shows the basic differences between these two terms.

In the IoT interconnected system, safety is not a huge deal because consumer data does not require any security. The security of industrial IoT is becoming a key element when it comes to data entry and transmission. The disruption of production systems that involve industrial IoT costs huge financial resources and disrupts the economic activity of a large number of people and processes. Therefore, industrial IoT solutions consist of a series of advanced security measures, using security and resilient system architectures, encryption and authentication, specialized chipsets and threat detection.

Industrial IoT solutions must coexist with older operating technologies such as SCADA, M2M and other production execution systems. It is difficult to make older operating technologies disappear quickly. Industrial IoT will replace them, but to do so, it must first integrate with them, so industrial IoT solutions must support different protocols and datasets. [7]

In the contrast to IoT solutions, the Industrial IoT solutions must be very precise and accurate. From data entry to analysis, accuracy and precision should not be compromised because the automatic high-speed, high-volume manufacturing processes are synchronized to milliseconds. The quality assurance systems detect small dimensional variations in the data and take an immediate course of actions which are entirely dependent on those measurements. In the Industrial environment, “close enough” isn’t good enough, and can cause downtimes, which ultimately results in lost revenues or loss of life.

4. DIGITAL TWINS - A CRITICAL MILESTONE TOWARD THE SMART INDUSTRY

Although the concept of a digital twin exists for quite a time, only thanks to the Internet of Things (IoT) it has become cost-effective for implementation.

Simply, the digital twin is a virtual model of a process, product, or service. This pairing of the virtual and physical worlds allows data analysis and system monitoring to solve problems before they even occur, prevent downtime, develop new features, and even plan for the future using simulations. [8]

The digital twin of an item is a computer image corresponding to a real one. It is created for each item during the design process, and then the digital twin is detailed during the production of the item and becomes its exact (in the ideal case) digital copy, which allows the reproduction of all the basic properties of the item. Then the digital twin goes through all the stages of the life cycle of a physical object.

Since the gear transmissions are among the most difficult mechanisms to calculate and design, the methods of their calculation, design and diagnostics have a general significance in machine building. Certainly, it is unrealistic to use a single and universal model that describes all the properties of a technically complicated mechanism, such as gear transmission.

Creating a digital twin based on a set of models and methods that reflect the transmission behaviour as a whole in functional and reliable aspects (lifetime mechanics) is an effective way to solve the problem of transmission design and maintenance during its life cycle. [2]

The central concept of Industry 4.0 is a cyber-physical system (CPS), which is characterized by a physical object, for example, a machine, and its digital twin, in the form of a model or a set of models that are implemented in software simulating the behaviour of the physical object.

Fundamentally, new parts in Industry 4.0 are components that are largely developed in mechanics. The most important ones are the model approach and the digital twin of the product, as well as sensor bases, wireless data transmission, diagnostics and analytics.

Digital twins are ready to transform manufacturing processes and offer new ways to reduce costs, monitor assets, optimize maintenance, reduce downtime and enable the creation of connected products.

Faults and defects of mechanical transmissions increase costs and overload employees in the production process. To alleviate these problems, manufacturers can use the digital twin, as one of the Industrial IoT functions. The digital twin replicates the mechanical transmission during its development into digital form. By upgrading the sensors, manufacturers collect data on the entire working mechanism of their equipment and the expected output of each unit. The data entered from the digital model allows manufacturers to analyze the efficiency, effectiveness and accuracy of the system. It also helps identify potential congestions in the production of a mechanical transmission, which helps the manufacturer create a better version of the product. [9]

The digital twin can allow companies to have a complete digital footprint of their products from design and development through the end of the product life cycle. This, in turn, may enable them to understand not only the product as designed but also the system that built the product and how the product is used in the field. With the creation of the digital twin, companies may realize significant value in the areas of speed to market with a new product, improved operations, reduced defects, and emerging new business models to drive revenue.

The digital twin may enable companies to solve physical issues faster by detecting them sooner, predict outcomes to a much higher degree of accuracy, design and build better products, and, ultimately, better serve their customers. With this type of smart architecture design, companies may realize value and benefits iteratively and faster than ever before. [10]

4.1. Approaches for creating digital twins

Three approaches can be distinguished when creating digital twins.

- The first approach considers general methodology for any field of application. The main tool is the use of big data and analytics. This approach is mainly used to improve items that have relatively short lifetimes. At the same time, models of workflows of items are not considered in detail. So, in one paper [11], operational data is used to improve the production process and service. Another paper [12] considers the possibility of applying operational data to the design process. Digital twin-driven product design (DTPD) is proposed and analyzed. DTPD is expected to be most useful for the iterative redesign of an existing product instead of a novel design or a completely new product.

- The second approach is based on the use of universal methods and software based on certain physical (mechanical, etc.) models. At the same time, modelling the workflow of an item is widely used. To simulate the behaviour of items, the finite element method and methods of multibody dynamics are widely used. Siemens AG gives typical examples of the second approach.

The digital twin can be considered as the virtual copy of a real-world asset. It integrates here with all data, models and other structured information related to the product, plant, infrastructure system or production process. This data can be generated during design, engineering, manufacturing, commissioning, operation or service. The fast adoption of the digital twin concept builds on advances in simulation methods, computing power, availability of IoT data and artificial intelligence. [13]

Two key elements of the digital twin are that it is holistic and dynamic. Holistic implies that all information is integrated and consistently consumed at various parts of the life cycle, connected through a digital thread. Dynamic implies that the digital thread grows over the life cycle, completing the system description and adding higher levels of detail when these become available and updating the underlying models based on the actual product use.

At its highest level, a digital thread is a continuous, seamless strand of data that connects each stage of the product life cycle from design, to build, to in-the-field usage. It provides, in effect, the channel through which data about the product travel. Such data—their storage, ready access, modelling, and analysis—are what create the ability to model production and drive efficient supply chain communications. [10]

- The third approach includes special models and methods related to specific objects. In this case, these are gears and transmissions.

Some papers give different modern representations of digital twins in the field of gears and transmissions. A paper [14] describes a simulation-based model meant to predict the fatigue endurance of tooth root. The model can be regarded as a digital twin of performance and enables the prediction of the fatigue behaviour of tooth roots even for conditions which are not covered by the standards yet.

One publication [15] describes an efficient and goal-oriented way, which presents the immense advantages of the use of digital twins, shown in the example of spur gear stage design, the definition of macro geometry and the final microgeometry optimization of the tooth flank.

Another paper [16] points out that nowadays a large number of different CAE tools are available for the design and analysis of a gear unit and its components, each of which has its own strengths. A major milestone for Industry 4.0 is the establishment of industry-wide standards. The German Research Association for Drive Technology (FVA e.V.), in close cooperation with industry and research, is developing an industry-wide standard for simple data exchange in transmission development under the name REXS (Reusable Engineering EXchange Standard). The REXS initiative pursues the goal of providing a “digital twin” in transmission development and calculation. REXS defines uniform parametric modelling and nomenclature of gear units and their components across standards and industries, based on detailed terminology from FVA’s 25 project committees and 50 years of joint industrial research.

This is meant to reduce the number of interfaces involved in the design process. This is the vision of the REXS initiative: a free, nonproprietary, standardized interface for the exchange of transmission data which reduces the complexity of data exchange in the design process significantly (Fig.4).

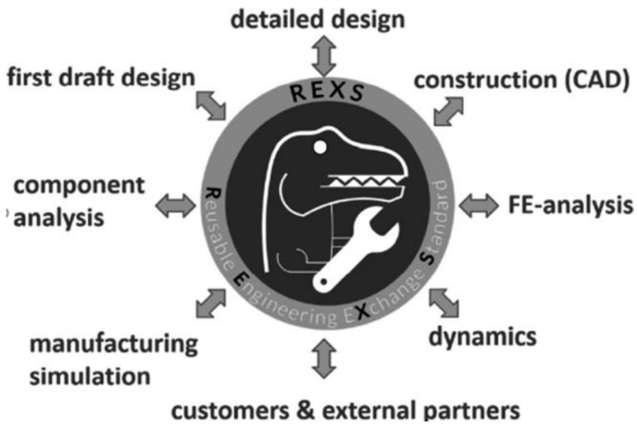

Fig.4. Design process with standardized interface REXS

REXS has the potential to establish itself on a large scale as a standard model for data exchange in the field of gear unit design and analysis. This would result in several advantages for the software manufacturers, for the companies using the tools and for the users:

1. Transmission designs and analyses at any level of detail, i.e. from the overall system view via the analysis of individual components to the individual physical phenomena, can always be carried out based on a single data model;
2. A simple data exchange between classic analytical gear design programs and universal dynamic, FE and CAD systems would be possible. Expenses for additional, specific modelling could be greatly reduced, etc.

4.2. Vision and understanding of the “Digital Twin”

The following aspects are essential:

- Each part of the machine is represented as a source of information signals;
- The machine units in which it is possible and appropriate to implement the principles of reflexive

control are allocated; procedures for the identification of information sources, control objects and reflexive nodes are provided, then their interdependences are determined.
The information model should be designed in such a way as to allow the use of various sources: semantic, structural (logical), parametric (quantitative, mathematical) models; measurement results; expert evaluations; means of simulating the elements and units of the machine (in slow, accelerated and real time scales in relation to the current, retrospective and predicted state).
Thus, the developed methodology anticipated one of the principles of Industry 4.0: the creation and use of an item's digital twin.
The assumption that there are possible conflicts among the subsystems of the machine, endowed with intellectual properties, can be considered as a forecast for the forthcoming Industry 4.0 technologies.
Modern authors' conception is depicted in Figure 5 [17]. This concept is presented in detail below in relation to gears and transmissions.

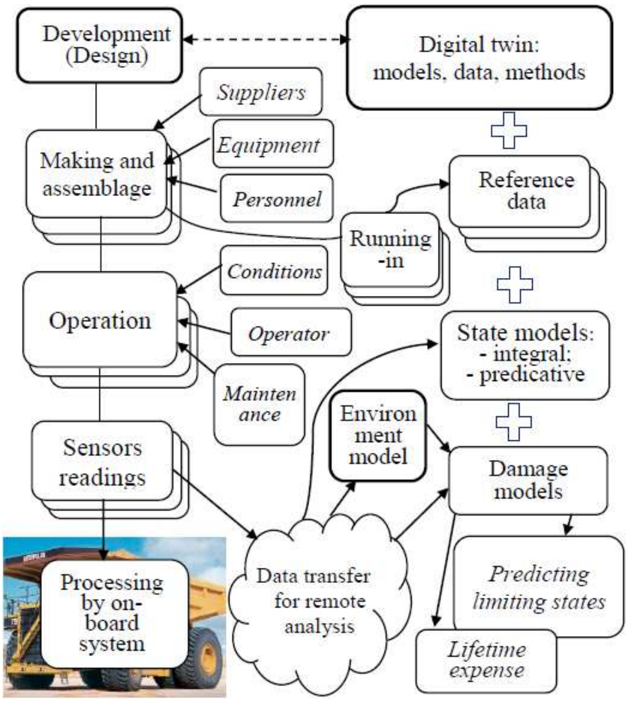

Fig.5. Evolution of the item and its digital twin during life cycle [17]

Fortunately, software tools are rapidly rising to the challenge of concurrently building and integrating digital twins. As the technology evolves, those tools will grow more powerful and sophisticated, and IoT-enabled digital twins will become more tightly integrated into a plant's production processes, and far more capable.
They will also become smarter, using machine learning programs, a type of artificial intelligence, to learn more about a factory's machines and improve the ability of digital twins to simulate and predict their behaviour.
As artificial intelligence systems learn more about specific machines, they will use their digital twins to help engineers run plants more efficiently. If there is some problem with a machine, artificial intelligence can analyze it to see what is wrong. The better the artificial intelligence knows the machine, the more accurately it can predict when that failure is likely to happen. [18]
The growing importance of digital twins in IoT projects today de facto is mainly mentioned in the scope of the manufacturing sector, the bridging of digital and physical worlds in Industry 4.0, the digital transformation of manufacturing and industrial markets overall, including smart supply chain management. As written previously, the usage of the IoT in manufacturing is the highest of all verticals from an IoT technology investment perspective. It's also thanks to IoT that digital twins become affordable and most certainly alter the face of manufacturing technology. [6]

5. PREDICTIVE MAINTENANCE – INCREASING UPTIME AND REDUCING RISKS

Predictive maintenance always seemed like the perfect use case for the Internet of Things (IoT), more specifically for Industrial IoT (IIoT) and environments where uptime of specific assets is critical and breakdowns can have important consequences for several reasons. Many of the main technologies that are mentioned in the context of the Industry 4.0 play a role in predictive maintenance (Maintenance 4.0, PdM 4.0) and its evolutions: big data, artificial intelligence, machine learning, IoT, cloud computing, data analytics and, increasingly, edge computing and digital twins.
Sensors and actuators are transducers (Fig.6). A transducer converts a specific signal which comes in a specific form of energy into another signal in a different form of energy. Sensors convert signals in areas such as heat, humidity, pressure, presence of gases, pressure, acceleration and so forth into a digital signal that gets sent to a control and/or data aggregation systems such as a sensor hub or gateway. They are the start of all IoT data capture and thus must be accurate. The exact types of sensors (there are over a hundred) depend on what should be achieved. In some IoT use cases, projects or devices there are only a few sensors (per connected device), in others there are often thousands.

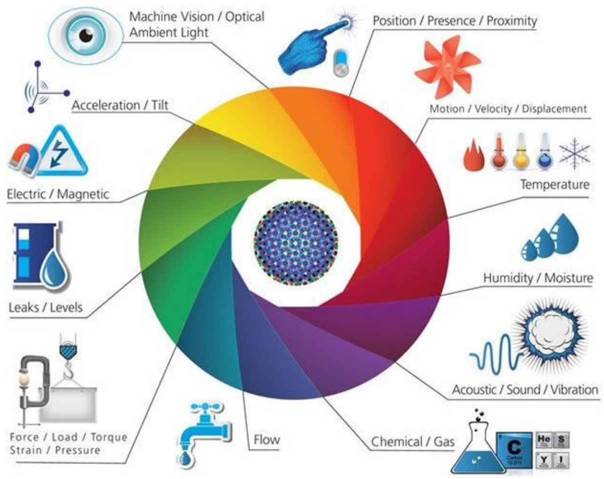

Fig.6. IoT devices – sensors and actuators examples [19]

Transmission systems of vehicles and tractors operate under conditions of varying speeds and loads. In addition to internal factors, external ones (the road surface, car loading, driver skills) influence on the vibration characteristics of transmission units. The main feature of the developed diagnostic method is using conceptual modelling for the oscillating process in the gear drive and the propagation of vibrations in the transmission. It is advisable to apply together integral diagnostic models and predictive ones based on damage accumulation. Such a ‘two-coordinate’ approach (two points of view) ensures higher veracity of the individual lifetime forecast. [2]
An example is a reducer of a motor wheel of a mining dump truck. The reducer of a motor wheel with installed sensors is shown in Figure 7, and processes in an onboard monitoring system are in Figure 8.

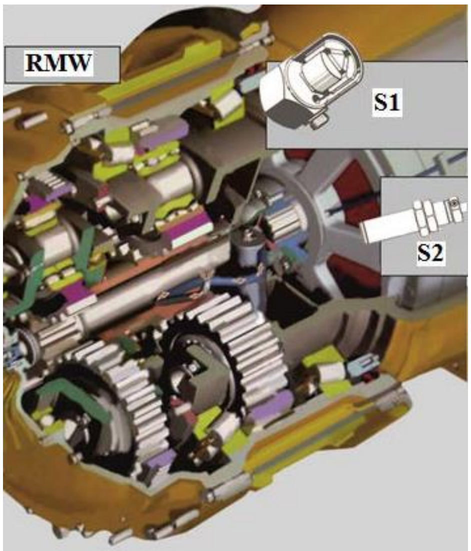

Fig.7. Reducer of a motor wheel with sensors [2]

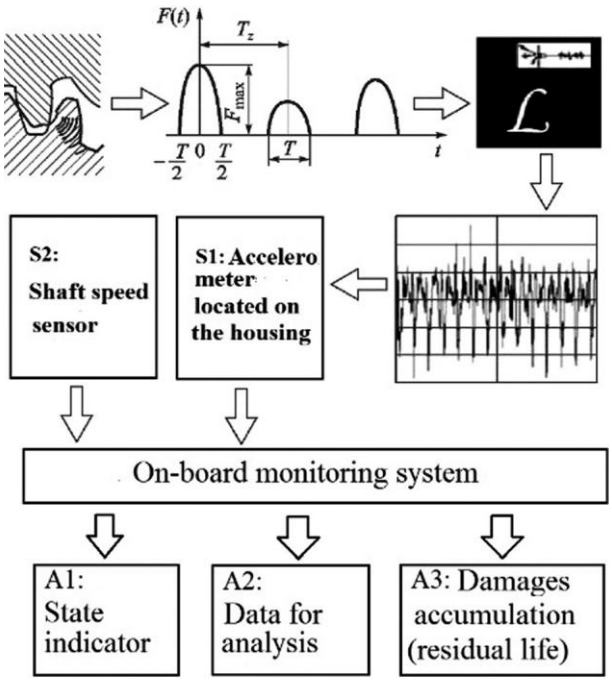

Fig.8. Processes in the RMW and its monitoring system [2]

Industrial IoT, in combination with predictive analytics and machine learning, however, are the main drivers of the more mature stage of predictive maintenance. Actionable, often real-time, data on pre-defined factors are gathered from smart sensors and predictive analytics algorithms are applied to predict when something might occur – and thus proactive maintenance, called predictive in this case, is needed.
The idea of predictive maintenance is simple and attractive enough and is similar to other forms of proactive maintenance with some additional benefits (and disadvantages): unexpected failure of equipment with all related consequences can be avoided, and maintenance can occur before something happens, instead of after the facts (reactive and run-to-failure maintenance), when such is deemed useful and possible. So, predictive maintenance is one of the maintenance methods enabling to do this kind of proactive maintenance and takes the most time and skills to implement. In other words: it’s important to use it where it makes true sense.
Typical goal statements of PdM 4.0:

- maximize utilization, minimize costly downtime,
- replace close to failure components only,
- enable just in time estimating order dates,
- discover patterns for problems,
- key performance indicator of asset condition,
- reduce risk.

Predictive maintenance uses machine learning engines with these parameters of the monitored equipment being used as a basis, but the actual difference concerning what the machine learning and predictions say is what is likely to occur within a specific time frame and with a specific probability. Typically, this also means that predictive maintenance uses more data sources and sets than the sensor data from condition monitoring and digitally recorded data from the previous stage, instrument inspection. The difference might seem small, but it’s not. Predictive maintenance uses monitoring data, but it uses more and, most importantly, it, indeed, predicts.
Almost all industries require effective tools or systems that help manage large data and use it to infer outcomes based on different situations. IoT technology comprises sensors and advanced gateway connectivity, which derive informed insights for the managers. It enables quick responses and better decision-making.
IoT promotes effective asset management strategies and enhances their performance by sharing valuable information with the managers. This helps reduce their workload of manually operating each task and rather automates the entire industrial processing. Hence, it leads to comparatively lower maintenance of the assets and simplifies the decision-making process. [19]
Keeping equipment in an operational state significantly reduces operating costs, saving the budget for manufacturers. Using sensors, cameras and data analytics, managers in several different product lines are now able to determine when a machine will break down before it stops. IoT-enabled systems can sense warning signs by using data that helps managers create maintenance deadlines and schedule equipment services before any problems occur.

Using real-time data from sensors and actuators, operations managers can quickly access current equipment conditions, recognize warning signs, receive alerts about problems, and get rid of wasting time into scheduling maintenance.
The sensor devices extract information from the assets and transfer the same through the gateway on the connected dashboard. This improves data storage on the cloud-based platform and processes it further in a user-friendly language, allowing effective productivity. The managers find this data easy to analyze and discuss the industrial flaws to encourage improvements in business strategies. [19]

6. DIRECTING THE DEVELOPMENT OF GEAR TRANSMISSIONS TO THE POSTULATES OF INDUSTRY 4.0

The function of driving systems is realized by the joint action of mechanics, sensors, actuators with appropriate information processing. Mechanics in this context should be understood as all components that directly participate in power transmission. Sensors and actuators also consist of mechanical components, but in this case, they represent the connection between the mechanics and the processor for processing information. With the help of sensors, it is possible to know the quantity of the actual values of individual operating parameters and transfer them to information processing systems. Information processing enables the successful control of power flow and work processes by comparing the actual and set values of the operating parameters of the system, and thus manages the system in order to fulfil its operating function.
Therefore, modern driving systems with these performances are in fact mechatronic systems, which in nowadays conditions of technical development are extremely important. The principle of driving systems operating is usually based on rotational or rotational-translational movement (transport mechanisms, industrial plants).
The power transmission system basically consists of three subsystems: driving engine, power transmission and operating machine. These subsystems consist of mechanical and structural elements. Gears, couplings, shafts, seals and bearings play the most important role in the synthesis of these subsystems.
These three subsystems form one oscillatory system, which is exposed to different influences, i.e. alternating loads. Vibrations negatively affect the successful execution of the system's operational function and can, in some cases lead to the appearance of a resonant state. Therefore, monitoring devices have to be installed in technical systems for monitoring the occurrence of vibrations and critical states of the components of the system.
There is a transmission of power and torque through the transmissions, so different forces occur on its components. In practice, various requirements are required from gear transmission. Thus, for example, in operating conditions, the direction of power flow can be changed, and thus the input and output of power are changed in transmission. There are often cases of branches aggregating or division of power. Particular structural elements often perform several different functions.
In practice, it happens that the constant gear ratio does not meet the working conditions, but it is necessary to bring power to several different places with different operating parameters. There are also cases where a change in both speed rotation and torque value in a wide range is required.
Progress in power electronics has made it possible to regulate speed electronically in some areas (for example a washing machine). Many mechanical couplings are replaced by the use of electronic controls, such as in production systems.
However, in many areas, power transmissions are irreplaceable, because they have many advantages: branching and summation of power, stepwise or continuous change of speed, reliable operation, energy efficiency and compactness of construction.
Driving systems are part of almost all types of machines and devices so the fulfilment of the work function in various areas of the industry depends on their reliable operation. If there is an aspiration to build smart factories, then the priority is the development and creation of smart driving systems. At the same time, it is a usual method not to change the design solution in the initial phase, but to install smart product systems in the existing solution of drive systems.
In this view, the following points should be considered:

- installation of sensors and software that enable full self-monitoring of the state of operating regularity of drive systems;
- installation of systems with integrated logic functions for monitoring the influential parameters of the operating machine and operating environment that affect the operation of drive systems;
- installation of a sensor module for data transmission and communication via IO-link, which as a result has a full connection with Industry 4.0.

For reliable operation of power transmission, it is very important to avoid critical conditions during operation. The risk of damage to the gearbox is reduced if the failures are detected at an early stage. Also, repair costs, as well as losses due to downtime, are avoided. For example, thermal stability and dynamic behaviour play a very important role in the reliable operation of the gear unit. It is the easiest to monitor them through temperature and vibration and to notice the exceeding of boundary conditions promptly through appropriate systems.

6.1. Digital transformation of universal helical gear reducers

The digitalization of helical gear reducers is transforming the business models and the manufacturing processes adopted by companies that operate in the industrial automation field. Such companies must meet requirements of more and more flexible production, in small batches, with high customization and short time-to-market, without giving up high technical performances and utmost quality levels. These gear reducer companies should make the effort of shaping a new automation era, more open, interconnected, intuitive and user-friendly. All this, thanks to the development of advanced products and technologies, concretely resulted in an innovative factory concept, called HUMANufacturing. This expression defines its way to Industry 4.0, where robots and the other industrial machines work in strict contact and in full safety with the operator, who remains central in the manufacturing process. [20]

Industry 4.0 has determined the need for a complete rethinking of production models that, from a “make to stock” logic, are evolving towards an “assembly to order” approach. Besides collaborative robots and other innovative products for industrial automation manufacturers have to develop solutions enabling the communication between operators and automation systems through mobile devices, developed according to the Industrial IoT vision. They are completed by preventive and predictive maintenance instruments. Such technologies are inspired by a right-sized automation strategy, aimed at an efficient balancing between machine use and human contribution in the productive context.

6.2. Innovative universal helical gear reducers – sensors installation

In order to be adopted for smart factories, universal helical gear reducer should be expected installation of following sensors:

1. Temperature sensor, which will monitor the oil temperature in the gearbox housing and if it reaches a boundary limit value then the sensor will "inform" the main processor. The system will assess whether the temperature rise is due to rising ambient temperature, in which the reducer is located, or due to a higher load of the reducer, which occurred due to a change in the technological process. The system will correct the operation of other components in the system and, if necessary, inform the operator, and in case of reaching a critical value, the processor will shut down the driving and, if necessary, the entire system in which it is installed.
2. Oil level sensor, which will monitor the oil level in the gearbox housing. In case of reaching a certain minimum value, the sensor signal will inform the system to add oil, or in complex and responsible systems, register the place of oil loss, and even performed automatic refuelling, and informed the system. In case of reaching a critical oil level value and loss of a large quantity of oil, the sensor would turn off the drive and also inform the system.
3. Vibration sensor, which will monitor the vibration level of the gearbox. If the vibration reaches the limit value, the processor would check the condition of other components in the system and check whether the cause of increased vibration is some external sources (some irregularity in the technological process) or an announcement of the forthcoming failure of some gearbox component. In the case the critical vibration value is reached, the sensor would timely prepare the shutdown system and turn off the gearbox and the entire system, if necessary. By applying special systems for vibration spectrum analysis, it would be possible to determine the cause of higher vibrations (bearing damage, gear damage, shaft bending, etc.) in responsible systems, which would speed up the elimination of the causes of elevated vibrations, or, if necessary, timely indicate for the implementation of appropriate activities.
4. Rotation sensor, which will monitor the rotation number of the output shaft (or gear). For example, in case the engine is running, and the output shaft does not rotate, the sensor would turn off the drive and immediately notify the system. Of course, this sensor would monitor the actual number of revolutions and in case of a significant change, through the appropriate processor, would conclude the need for a change in the transmission process, or would adjust the number of revolutions to adapt to new ones.
5. The operating time sensor, which will monitor the operating time between two oil changes. When it passes the estimated time for replacement, it will notify the system.
6. Total operating time sensor, which monitors the total operating time of the gearbox, in order to indicate the performing the service, i.e. mandatory repairing the gearbox or to indicate the period of occurrence of possible gearbox failures.

In the future, motor gearboxes, i.e. their electric motors, will certainly be, even more often than before, equipped with drive control devices (usually frequency regulators) which would automatically adjust the speed of the gearbox output shaft to the requirements of the technological process under full load. Electric motors will be supplied with processors that provide the so-called soft start so that there are no sudden impacts during the start that significantly shorten the service life of the gearbox.

1 2 3

Fig.9. Innovative solution of universal single-stage helical gearbox: (1) solution of company REGAL [21], (2) solution of company STM TEAM [22], solution of company PGR [23]

Despite the fact that the current solutions of universal gear reducers have very good design solutions, their appearance will have to be paid even more attention because all other parameters (quality, price, delivery times, etc.) for most gear manufacturers, will be similar. [24] Therefore, the appearance solution of gears will greatly affect their placement. For example, today the solutions of single-stage motor gearboxes of the company REGAL (Fig.9-1) are especially interesting. The design of single-stage gearboxes of companies STM TEAM (Fig.9-2) and PGR (Fig.9-3) are also interesting. Similar solutions can be expected from other gearbox manufacturers in the future.

Interesting design solutions for two-stage helical gear reducers are solutions of company SESAME (Fig.10-1), Stöber (Fig.10-2) and BEGE (Fig.10-3).

1 2 3

Fig.10. Innovative solution of universal two-stage helical gearbox: (1) solution of company SESAME [25], (2) solution of company Stöber [26], (3) solution of company BEGE [27]

Interesting design solutions for three-stage helical gear reducers are solutions of the company Siemens (Fig.11-1), Motive (Fig.11-2) and Rossi (Fig.11-3). Also, there are innovative solutions in other types of gear reducer mounting, for example, shaft-mounted gearbox with axial mounting, but also in other types of gear transmission (bevel, worm, harmonic, etc.).

1 2 3

Fig.11. Innovative solution of universal three-stage helical gearbox: (1) solution of company SIEMENS [28], (2) solution of company Motive [29], solution of company (3) ROSSI [30]

1. CONCLUSION

The goal of Industry 4.0 is to enable autonomous decision-making processes, monitor assets and processes in real-time, and enable equally real-time connected value creation networks through early involvement of stakeholders, and vertical and horizontal integration.

Industry 4.0 represents the digital transformation of manufacturing. Its most important benefits and potential perspectives are enhancing productivity, automation and the optimization of operational processes, business processes, and manufacturing operations, followed by (predictive) maintenance and smart maintenance services. In order to move to intelligent manufacturing, smart factories, or connected industries, it should bridge things such as real things, people, standards, work processes (man and machine) and more. Moreover, to bridge all that need data and networks. They must all inter-operate and inter-connect. It should bridge IT and OT, have assets such as machines that can connect and communicate thanks to sensors and other equipment and connect people, data, and machines. This is indeed mainly about the Internet of Things and, in a broader perspective the Internet of Services, Internet of People, Services and Things and Internet of Everything.

The digital twin may drive tangible value for companies, create new revenue streams, and help them answer key strategic questions. With new technology capabilities, flexibility, agility, and lower cost, companies may be able to start their journeys to create a digital twin with lower capital investment and shorter time to value than ever before. A digital twin has many applications across the life cycle of a product and may answer questions in real-time that couldn’t be answered before, providing kinds of value considered nearly inconceivable just a few years ago. Perhaps the question is not whether one should get started, but where one should start to get the biggest value in the shortest amount of time, and how one can stay ahead of the competition. What will be the first step, and how will it get started? It can be an overwhelming task to get there, but the journey starts with a single step. [10]

The beginning of the period of Industry 4.0 was conditioned by using communication between cyber-physical systems and the internet of things (IoT) and all other parts of the production process. Having all that in mind, it can be concluded that further development of gear transmissions will be aimed at the greater application of artificial intelligence and machine learning, primarily various sensors and processors that will monitor and regulate their work and communication with other segments within the same technological process. These smart gearboxes will have a nice appearance design and high-class technical characteristics, with applied product personalization and customization and a short delivery time.

REFERENCES

[1] Kuzmanović, S., Miltenović, V., Rackov, M., Innovative design solutions of universal motor gearbox with helical gears, International Scientific Journal Machines. Technologies. Materials., Vol.14 (2020), No.4, pp. 137-141, Publisher: Scientific Technical Union of Mechanical Engineering "Industry-4.0", Sofia, Bulgaria, Editor In Chief: Prof. D.Sc. DHC Georgi Popov, ISSN 1313-0226, E-ISSN 1314-507X

[2] Algin, V., Ishin, M., Paddubka, S., Starzhinsky, V., Shil'ko, S., Rackov, M., Čavić, M., Development of information model of power transmissions in the light of Industry 4.0, International Scientific Journal Mathematical Modeling, Vol.4 (2020), No.2, pp. 54-63, Publisher: Scientific Technical Union of Mechanical Engineering "Industry-4.0", Sofia, Bulgaria, Editor In Chief: Prof. Andrey Firsov, ISSN 2535-0986, E-ISSN 2603-2929

[3] Miltenović, V., Antić, D.: Inženjering pametnih proizvoda i usluga, Univerzitet u Nišu, Niš, 2020.

[4] Bojan Stanojević, 2016. Industrija 4.0 i budućnost, 2016 [online]. PCpress magazine. Available: https://pcpress.rs/industrija-4-0-i-buducnost/ [accessed 12th April 2022]

[5] CIRP Encyclopedia of Production Engineering. Int. Academy for Production Engineering, Laperriere, Luc, Reinhart, Gunther (Eds.) 2015

[6] https://www.i-scoop.eu/industry-4-0/ [accessed 12th April 2022]

[7] https://www.biz4intellia.com/blog/differentiators-of-industrial-iot-and-iot/ [accessed 12th April 2022]

[8] Marr, Bernard (March 6, 2017). What is Digital Twin Technology - And Why is It so Important?. Forbes.com.

[9] https://www.biz4intellia.com/blog/iot-applications-in-manufacturing/ [accessed 12th April 2022]

[10] https://www2.deloitte.com/us/en/insights/focus/industry-4-0/digital-twin-technology-smart-factory.html [accessed 12th April 2022]

[11] F. Tao [et al.], Digital Twin driven Product Design, Manufacturing and Service with Big Data, International Journal of Advanced Manufacturing Technology. 2017. 1–14. DOI: 10.1007/s00170-017-0233-1.

[12] F. Tao [et al.], Digital twin-driven product design framework, International Journal of Production Research. 2018. 1–20. DOI: 10.1080/00207543. 2018.1443229.

[13] Van der Auweraer, Digital Twin: From Concept to Value Creation across the Product Lifecycle, 15th IFToMM World Congress, 30 June – 4 July 2019, Krakow, Poland: Program. 2019.

[14] Meis, J-A., F. Teklote, M. Borowski, Simulation of the tooth root strength under consideration of material quality, finishing process and size effects, International Conference on Gears, Garching, Munich, Germany, September 18–20, 2019. pp. 161–171.

[15] Algin, V. Dependability of technically complicated items in the light of “Industry 4.0”, V. Algin, M. Ishin, Topical issues of Mechanical Engineering. 2017. No. 7. pp. 43–54 (in Russian).

[16] Khizhenok, V. Strain-strength characteristics of the polymer heart valve prosthesis, V. Khizhenok, S. Shilko, Russian Journal of Biomechanics. 2006. 10(4). pp. 47—55.

[17] Algin, V. Dependability of technically complicated items in the light of “Industry 4.0”, V. Algin, M. Ishin, Topical issues of Mechanical Engineering. 2017. No. 7. pp. 43–54 (in Russian).

[18] https://www.asme.org/topics-resources/content/identical-twins [accessed 12th April 2022]

[19] https://www.i-scoop.eu/industry-4-0/predictive-maintenance-pdm/[accessed 12th April 2022]

[20] Bonanomi, A., Industry 4.0: Driving Engine of Innovation, Power Transmission World (25 July 2018)

[21] Marathon Gearboxes Inline Coaxial Catalogue, Regal Beloit Australia Pty Ltd (2018)

[22] STM TEAM catalogue, CT17 IGBD 3.1 | ITA - ENG – DEU, 3/2018

[23] PGR Drive Technologies, Catalogue Helical Gear Units, PA/PF series 02/2019

[24] Rackov, M., Kuzmanović, S., Blagojević, M., Đorđević, Z.: Helical motor gear reducer (monography in Serbian), Faculty of Technical Sciences, Novi Sad, 2019.

[25] https://www.sesamemotor.com/en/products/detail/18

[26] SMS/MGS Gearunits, Catalogue 11, STÖBER Antriebstechnik GmbH & Co. KG.

[27] BEGE Power Transmission, Catalogue no. 241704, Helical Gear Motors, Sassenheim, Netherlands

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FAMILY DEVELOPMENT PROCESS – „TYPISATION" IN MACHINE DESIGN ON THE EXAMPLE OF CARDAN SHAFTS

Zoran STAMENIĆ

Abstract: *Owing to the use of computer technology and increasingly advanced simulation and optimization software, the design process has improved significantly in recent decades. In this process, traditional methods are often neglected in the design phase, especially if it is necessary to design and develop families of standardized products (machine parts or assemblies) which have the same shape and material, but different dimensions and load capacity, based on the parent design. An example of the use of typization as a traditional method of design is presented through the study of the influence of load distribution and operating conditions on the operational ability of Cardan joints, by modifying the geometry of the Cardan cross. For the purposes of the study, a certain number of Cardan couplings from several different manufacturers were tested and it was noticed which manufacturer complied with all the guidelines for the development of a typified family, where members have different geometry, dimensions and load capacity.*

Keywords: *Product development; product family; geometry of Cardan joints*

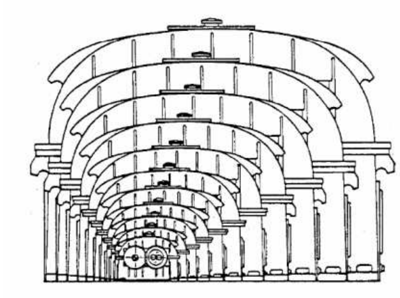
1. INTRODUCTION

In the research of the influence of the change in the geometry of the Cardan cross sleeve on the load distribution, in the experimental part and mathematical model from several manufacturers, deviation from the law of similarity (geometric and Cauchy) was observed in developing the family of Cardan couplings of different dimensions and LOAD capacities. It is shown how the change in the geometry of the Cardan cross sleeve, in one manufacturer affects the performance as expected, in accordance with the typified series, and in other manufacturer, the change is not so precise [1].

Modern machine construction must meet increasingly stringent criteria in terms of capacity, reliability, safety and security. In addition, the criteria from the aspect of ecological, energy and economic efficiency are more and more represented nowadays. Accordingly, new calculation procedures, materials, manufacturing technologies and design procedures are required, which will meet the above criteria. The designing, testing and machine manufacturing processes can be greatly accelerated by applying the Geometric and Cauchy's similarity criterion. By applying Cauchy's similarity criterion, families of typified design solutions, of the same shape and material, but with different dimensions and load capacity are developed. According to this criterion, one designed and tested machine structure (parent design) can be transformed into a family of similar machine structures, with larger or smaller dimensions and load capacities, without further testing and designing. In order to realize this transformation process, the physical sizes of all members of the typified series change in proportion to the changes of their dimensions, and the numerical values of these sizes belong to a set of standard numbers.

2. TYPISATION IN THE DESIGN PROCESS

In mechanical engineering, there is often a need for the design and production of a number of machine parts, subassemblies and assemblies of uniform shapes and materials used, but different in dimension and load capacity, Fig. 1. Typical examples of typified components are electric motors, gearboxes, pumps, compressors, fans, etc. One of the basic activities within the standardization is the products typisation. Accordingly, typisation is a form of standardization in which the product assortment is reduced to the most favorable range. It is carried out in order to increase the massiveness and quality of production while at the same time increasing the economy, profitability and productivity. Also, typification process facilitates the exploitation of mechanical systems, as well as their maintenance and supply of spare parts.



(a)

(b)

Fig.1. Application of typisation process in the development of a series of gear box housing (a) [2] and turbochargers (b), standardized diameters of the impeller are from the order R40/3 with the growth factor φ_L = 1,18 [3]

The typisation is based on the application of the criterion of geometric similarity, the Cauchy's similarity of loads criterion and a set of standard numbers. Instead of designing a series of machine parts, subassemblies and assemblies of the same function and of different capacities, only the parent machine structure, most often the smallest member of the typified family, is designed. Through the phases of the designing process, the shape, dimensions, material and tolerances are defined, and, in the end, the appropriate technical documentation is generated. Then, the same, parent machine structure is produced and thoroughly examined in working conditions, in order to examine and correct possible deficiencies. Then, without the application of the designing process, but only on the basis of the results of constructing and testing the parent machine structure, the geometric quantities and the load sizes (power, flow, load, etc.) are defined for other members of the typified family. Bearing in mind the fact that the parent construction leaves all its good and bad characteristics in the heritage to its descendants, it must be a "mature construction", that is, it must be fully constructively and productively perfected [2, 4].

2.1. The criterion of geometric similarity

If the index "0" indicates the quantities that refer to the model, and without the index of sizes that refer to the actual machine part, then the geometric similarity is expressed by the conditional constancy of length measures – geometric similarity factor:

$$\frac{L}{L_0} = \varphi_L{}^2$$

Based on the of geometric similarity factor, all factors of the geometric characteristics can be defined such as: surface area similarity factor, volume similarity factor, moment of inertia similarity factor, mass similarity factor, dynamic moments of inertia similarity factor, etc.

2.2. The criterion of geometric similarity

Cauchy's similarity condition provides a relationship between the load of the model and the load of the object depending on the geometric similarity factor. The machine part and its model made of the same materials must have the same safety factor, in order to have the same working ability. Hence, follows corresponding factors of: safety, critical stress, operating stress, force, moment, acceleration, time, velocity, power, etc.
If a family of machine parts or products with *m* members is formed, in the range of the operating characteristics from $N_{\min}$ to $N_{\max}$ then it can be defined growth factor *N*:

$$\varphi_{\mathrm{N}} = \sqrt[m-1]{\frac{N_{\max}}{N_{\min}}}$$

In order to be able to express the growth factors for other physical quantities (surfaces, volumes, axial moments, loads, mass, etc.) in the function of the growth factor of the length measure, it is necessary that all length dimensions (length, width, height, diameter, etc.) with the observed typified parts have the same growth factor. All calculated values have to be standardized by applying the series of standard numbers or geometric progression.

3. CARDAN JOINTS

Cardan joints (Cardan shafts) have a large range of applications in mechanical engineering because of the capability of transferring the load and motion from one shaft to another with different joint angle allowing, thereby, over time relative movement. This movement can be angular and translational. The main parts of Cardan joint are: two forks, four bushings with needle bearings and Cardan cross, as shown in Fig. 2. Due to specific operational conditions, the vital parts of these joints have a limited service life. The complex geometry, kinematics and dynamics of these joints, contributed to the certain number of research and papers. Service life of Cardan coupling primarily depends on the surface strength of the area of rolling elements contact surfaces, i.e., their ability to oppose to different types of failure.
On the contact surfaces of gear pairs ISO standard [5] registered over 20 different forms of fracture and damage. Almost the same types of damage are present at the contact surface of roller bearings and Cardan couplings. Such a large number of failure forms and contact damage of rolling elements surfaces is the result of a large number of influencing factors on their surface hardness: conditions of formation of contact surfaces, shape tolerances of rolling parts, roughness, load distribution on the simultaneous parts in contact; load distribution along the contact line, surface hardness, lubrication conditions, a burn conditions.

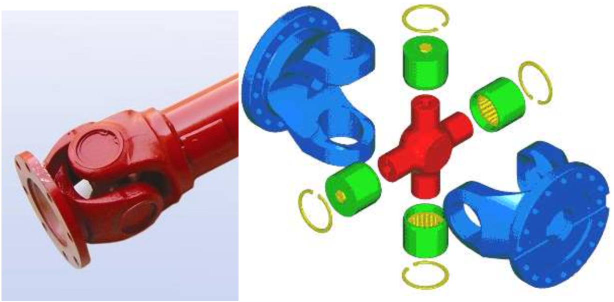


Fig. 2 Cardan coupling assembly

The greatest influence on the strength of the contact surface has a load distribution along the line of contact and load distribution of rolling parts simultaneously [6]. With increasing a degree of uneven distribution of the line load strength, decreases the strength of contact surface, which reflects the increasing intensity of various forms of failure. It should be noted that one aspect of the failure and produced particles of material, accelerate the development of other types of damage on contact surfaces. Compared with other machine elements, roller bearings and gear pairs, Cardan coupling components have the most unfavorable geometric and kinematics conditions in terms of uniformity of load distribution along the line of contact. Even in ideal conditions, the geometric accuracy of parts in contact of Cardan coupling, on the contact surfaces can not be achieved uniform load distribution. The main reason is the extremely unfavorable position of the contact line of rolling parts in relation to the direction of the angular velocity vector. The points of contact that are farthest from the axis of rotation first come into contact [6]. These are the points on the top of the sleeve on Cardan cross pin. The degree of involvement of other points of contact line depends on the geometric characteristics of bearing rolling parts, the contact deformation and the intensity of the service load. Theoretical and experimental studies have shown that parts of the pin sleeve near its root almost always remain intact, because they do not participate in the load transfer. Thus, the central problem in Cardan coupling is to reduce the uneven load distribution along the line of contact of rolling parts, or to unload parts on the top of a cross pin sleeve. According to this, based on previous researches, the two design solutions were formed. The first solution is based on the correction of rolling parts contact line - the needles. This correction involves the correction of the geometry of needles ends. Another solution is based on the use of two rolling parts in line - shorter needles instead of one long needle.

3.1. Geometry and loads of Cardan joint rolling components

In order to study the load distribution in Cardan joints assembly, an appropriate geometric model has developed. According to this model, the influence of geometrical parameters of rolling parts on the linear load distribution was analyzed. The analyses of obtained results should identify the optimal geometry of rolling parts in terms of uniformity of linear load distribution. With developed numerical model (FEM), the influence of load on the contact stress state of rolling components in contact was analyzed.

Cardan coupling load is in the form of tangential force F_t which is caused by torque transmitted by coupling. This force is orthogonal directed at Cardan cross axes but distributed not evenly along the line of contact at rolling components. The biggest intensity of nominal load is at points which belongs to the sleeve root, diagram in Fig. 3.

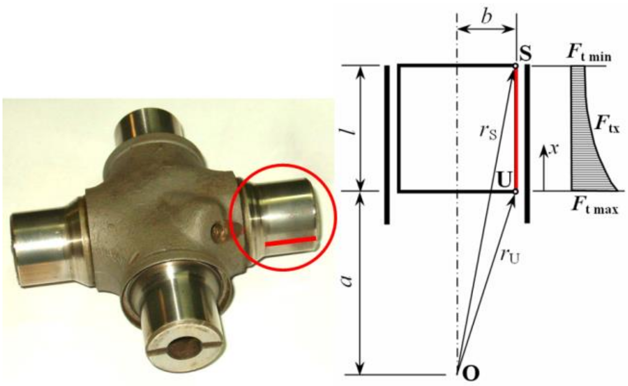


Fig. 3. Load distribution along Cardan cross sleeve lateral line

The lowest intensity of load is at points which belongs to the top of the Cardan cross sleeve. The difference between these boundary of load values depends on Cardan cross geometry. For the purpose of define the influence of geometrical parameters on the degree of uneven load distribution along sleeve lateral line, the appropriate analytical expression is formed. The load ratio in form of tangential forces in a random point (**X**), Fig. 3, on sleeve lateral line is observed according to its maximum value:

$$\frac{F_{tx}}{F_{tx\max}} = \frac{1}{1 + k \cdot \frac{l}{a}}$$

Where: $k = x/l$

A higher degrees of uneven load distribution corresponds to larger values of parameter ***k*** and to the ratio ***l/a***. Lower gradient of load decrease from the root to the top of a Cardan cross sleeve corresponds to small values of ratio ***l/a***. This means that the degree of uneven load distribution on a sleeve will be smaller, if a sleeve is more distant from the bearing axis.

In Cardan joints rolling components in contact, length of contact lines and degree of engagement of some of its points, are significant function of sleeve geometrical parameters, i.e. distance between points on contact line from the axis of rotation. During load transfer, points of the sleeve top first make contact. The degree of engagement of further sleeve points depends on geometric characteristics of rolling elements in contact, stiffness and value of load. At the same time, points of the sleeve root almost always remain unloaded. Because of their unfavourable geometry and mutual position of elements in contact, a points of the sleeve root fails to form a line of contact. Thus, the dominant condition to achieve more even linear load distribution is the formation of longer contact line along a lateral line of sleeve in load free state. The correlation between the displacement of sleeve lateral line points and geometric characteristics of sleeve, diameter and sleeve lenght as well as a sleeve distance from its axis of rotation, is established. For forming this correlation a geometrical model was observed which is shown in Fig. 4.

In the presence radial clearance Z_l, point **S** on the top of the sleeve, to establish contact with the appropriate point on the opposite part in contact - bushing, must be rotated around the axis **O** for elementary angle $\Delta\psi_s$. Correspond to this Cardan cross turning angle, is elementary path - elementary arch movement of point **S** for the value **SS'**, Fig. 4. At the same time, the turning angle $\Delta\psi_u$, is equal to elementary path – elementary arch movement of point **U** for the value **UU'**.

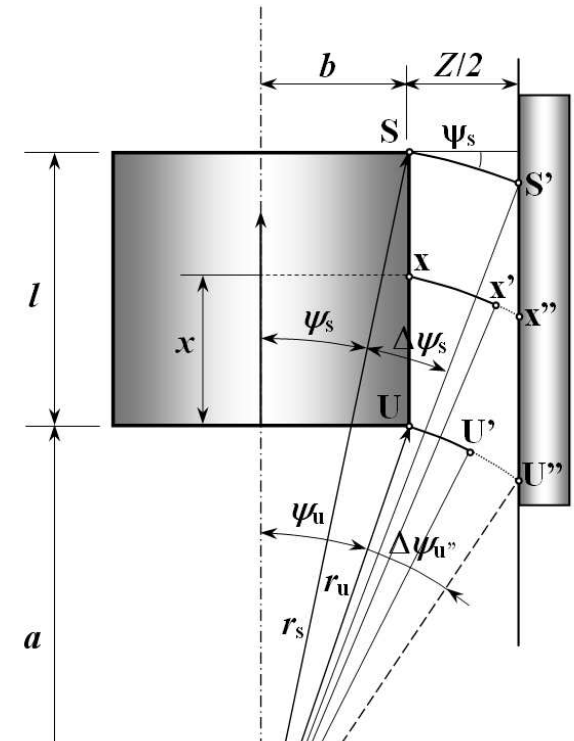


Fig. 4. Geometrical model of Cardan cross parts in contact

Point **U** in sleeve root, for establishing a contact with appropriate point of the opposite rolling part in contact – needle, has to rotate around the axis **O** for elementary angle $\Delta\psi_{u''}$. To this angle of rotation, correspondent is elementary path - elementary arch movement of point **U** for the value **UU''**.

Displacement of point U in a sleeve root for value of UU', and point S on the sleeve top for value of SS', is the moment of rolling parts contact. This primary contact of rolling parts in point S' was achieved without load influence. In order to achieve contact of other points on the sleeve lateral line with the corresponding points on the rolling part (e.g. a random point X' with point X''), an additional turning for appropriate angle is needed. For point U it is angle $\Delta\psi_{u'-u''}$, and for point X' is angle $\Delta\psi_{x'-x''}$. The values of these rotation angles, if fact their angular displacements U'U'' and X'X'' depends on the geometrical parameters of rolling parts in contact. These additional angular displacements of sleeve points are provided with elastic deformation of rolling parts in contact, under the load. The values of these deformations are small and limited by the elastic properties of parts in contact, with its geometry and load intensity. According to this, the values of angular displacements U'U'' and X'X'' should be as small as possible. The amount of those displacements is dictated by the geometry of rolling parts. Therefore, the engaging of certain sleeve points in the load transfer primarily depends on the geometric characteristics of rolling parts in contact. To analyze the influence of geometrical characteristics of the rolling parts on the linear load distribution, the angular displacements of points on the sleeve lateral line are observed.

Based on the geometric model in Fig. 4, for the angular displacement of point **S** on the sleeve top, and some point **X** on sleeve lateral line rotation for angle $\Delta\psi_s$, **the geometric factor of linear load distribution G_r** is defined as:

$$G_r = \frac{XX_1}{SS_1} = \sqrt{\frac{1+2k\left(\frac{l}{a}\right)+k^2\left(\frac{l}{a}\right)^2+\left(\frac{b}{a}\right)^2}{1+2\cdot\left(\frac{l}{a}\right)+\left(\frac{l}{a}\right)^2+\left(\frac{b}{a}\right)^2}} \tag{1}$$

Where:

d – sleeve diameter

l – length of sleeve

$b = \frac{d}{2}$

$k = \frac{x}{l}$

By varying the values of the parameter k in the interval $k\in[0...1]$, according to expression (1), the influence of geometry on sleeve linear load distibution can be analysed. For example, for k=1, factor G_r reaches its maximum value $G_{r1} = 1$.

Small values of factor G_r, generates long arc length U'U'' requiring extensive additional sleeve rotation, which is providing from elastic deformation of rolling parts. Since these deformations are relatively small, additional sleeve rotation will not be enough to generate adequate length of rolling parts contact line. As a result, the load linear distribution will be very uneven, Fig. 6.

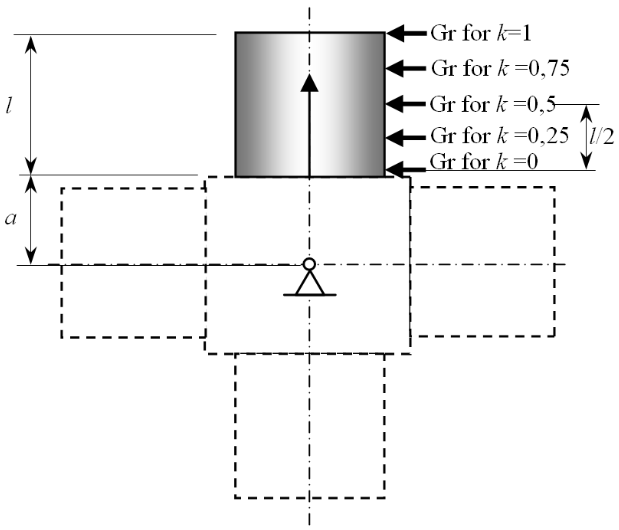


Fig. 5. Factor G_r dependence on geometric quantities of parts in contact

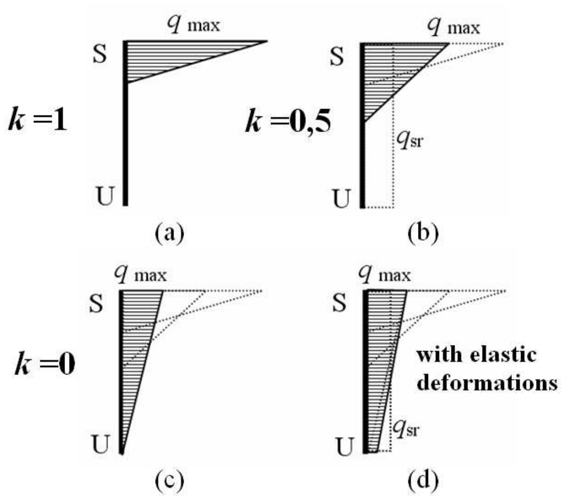


Fig. 6. The dependence of factor G_r from the geometrical values of rolling elements in contact and the theoretical linear load distribution for values of factor $G_r \leq 1$

Increasing values of factor G_r, reduces the length of the arc U'U". This reflects in increasing of the length of the theoretical lines of contact and reduces the degree of uneven load distribution. When the geometric factor of load reaches the value G_r=1, then the theoretical length of the contact line reaches its maximum value, equal to the length of the lateral lines of sleeve. At the same time, the degree of uneven loading is reduced. With increasing of load, due to contact deformations, triangular load distribution is transformed into trapezoidal. To obtain a better load distribution along the line of contact, it is necessary to ensure proper compatibility between geometric values of rolling parts and the contact deformation due to external load.

In continuation of these research it is needed to examine the real value of G_r factor, which can be achieved based on the geometric characteristics of rolling parts (*l, b, a*). For this purpose, by varying the ratio of geometric values of rolling parts (*l/a, b/a*), values of factor G_r were analyzed.

In order to analyze the influence of the linear load distribution on the operational capacity of Cardan joint rolling elements in terms of surface load, the numerical simulations of the contact load on the contact surfaces of journal sleeves and bushings of the Cardan cross was carried out. A plane model of Cardan cross sleeve and bushings of Cardan cross assembly is considered, and only one of four sleeves, because the same load image is repeated on each of them.

Fig. 7 shows the inclined plane model of Cardan cross sleeve. The elementary surface of the sleeve, which is in contact with a corresponding surface of the bushing is specially emphasized. It also shows the diagram of stress value variation along the center line on the sleeve contact surface. Presented stresses are the result of the pressure in the contact surface, as well as the effect of sleeve bending. Therefore, in the root of sleeve a stress values are increased.

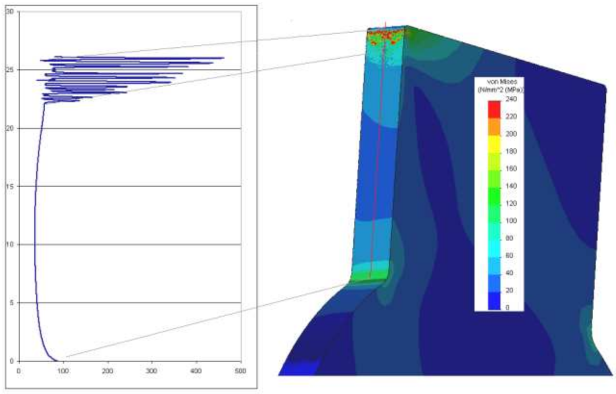


Fig. 7. The stress states on the contact surface of the Cardan cross drive sleeve and bushing surface

Input data for numerical analysis of stress states and loads of Cardan joints were obtained experimentally. Geometric characteristics of experimentally tested Cardan couplings were taken from production programs of different manufacturers. Eleven Cardan shafts samples of 4 types of different dimensions from 2 manufacturers, were tested, Fig. 8.

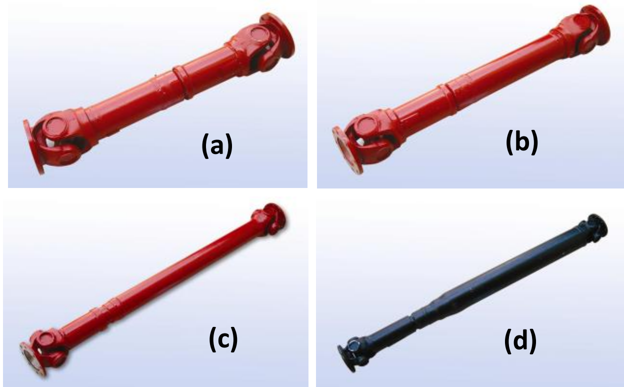


Fig. 8. Four types of Cardan shafts of different manufacturers; (a) and (b) manufacturer A; (c) and (d) manufacturer B

Based on the analysis it can be concluded the highest stresses (200…240 N/mm^2) are generated in the points that belong to the top of the sleeve (k = 0,75 ... 1,0). The minimum stress values should be at the base – the sleeve root. However, because of the influence of stress due to sleeve bending, the smallest stresses are generated in the middle area of the sleeve, k = 0,5.
In the contact surface upper zone the contact of rolling elements is achieved, therefore, this is the zone with the greatest intensity of stress. Because of the iterative calculation procedure, contact surface is not continuous but consists of a number of local points where stresses are concentrated. The values of the equivalent (*von Mises*) stress are shown, or strains along the contact surface of pins and bushings.
The obtained results shows, that with the standard (the existing) geometry of rolling parts, the engagement of points in root of Cardan cross journal in the load transfer is negligible due to very uneven linear load distribution. This unfavorable distribution of the linear load can be reduced with an appropriate combination of geometrical parameters of rolling parts in contact. Greater improvement of linear load distribution requires the appropriate shape reconstruction of rolling parts.

3.2. A shape reconstruction of Cardan cross sleeve

In order to find the geometric characteristics which will generate of the longer contact line, an appropriate geometric model is formed. The idea is simplify presented on Fig. 9 [1].

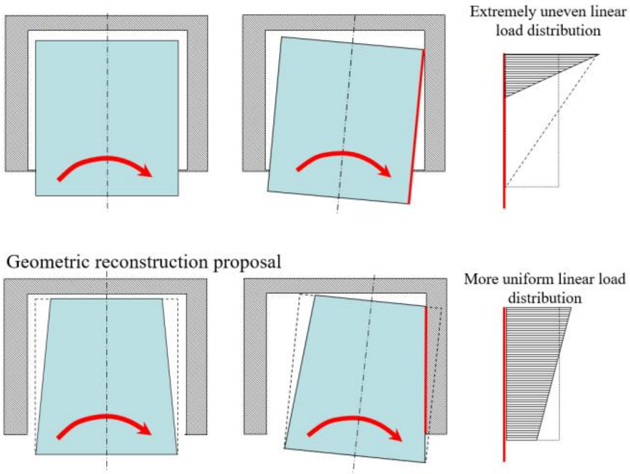


Fig. 9. A geometric shape reconstruction of Cardan cross sleeve

According to this idea, the new geometric and mechanical model is formed, Fig. 10.
In standard Cardan coupling designs, the radial clearance Z between the sleeve and the roller body has a constant value in the direction of the sleeve axis. The previous analysis showed that with the construction solution, with the standard geometry and shape of the cross axle sleeve (Fig. 4), simultaneous contact of its tip and root with the contact body (needle) cannot be achieved, which is a basic precondition for reducing uneven distribution along contact lines.

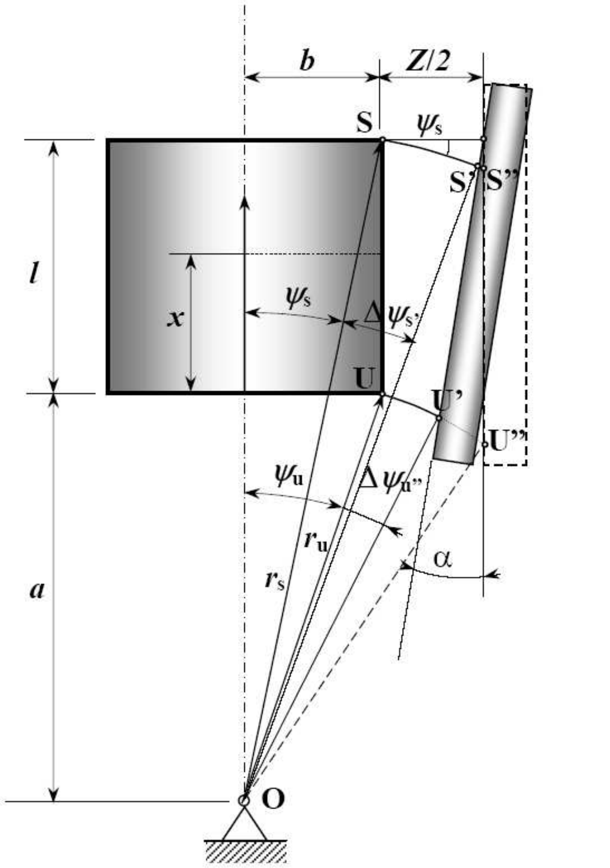


Fig. 10. A new geometrical model of Cardan cross parts in contact

In order to improve the load distribution along the contact line, an appropriate change in the radial clearance in the direction of the sleeve axis should be provided, which can be achieved by making the sleeve, or the inner surface of the cone-shaped bushing. This design solution can ensure simultaneous contact of the points at the top and at the root of the sleeve with the rolling body.
The further analyses show which angle α the roller body should be rotated, according to the model in Fig. 10, so that point S' at the top of the sleeve and point U' at the root of the sleeve come into contact with the roller body at the same time. In order to get an answer to this question, the ratio of the rotation angles of the point S to the point S' and the point U to the point U' was observed:

$$\frac{\Delta\psi'}{\Delta\psi_{S'}} = ?$$

Relations and transformations of equations from Fig. 10, the ratio of the rotation angles of the point S to the point S', and the point U to the point U' is obtained:

$$\frac{\Delta\psi_{U'}}{\Delta\psi_{S'}} = \frac{1}{G_{r0}} \cdot \frac{\frac{1}{\cos\psi_U} - \left(\frac{2l}{Z} + tg\,\psi_U\right)\cdot \sin\alpha}{\frac{1}{\cos\psi_S} - tg\,\psi_S \cdot \sin\alpha}$$

Where: G_{r0} - is the geometric factor of load distribution.

From condition:

$$\frac{\Delta\psi_{U'}}{\Delta\psi_{S'}} = 1,$$

follows an expression for determining the value of the angle α which will, for a given geometry of the connected parts and the size of the radial clearance, enable the simultaneous contact of points at the root and at the top of the sleeve with the rolling body:

$$\alpha = \arcsin \frac{\dfrac{1}{a \cdot \left(\dfrac{a}{l}+1\right)}}{\dfrac{1}{r_U} \cdot \left[\left(2\left(\dfrac{l}{Z}\right)+\left(\dfrac{b}{a}\right)\right) - \dfrac{1}{G_{r0}} \cdot \dfrac{1}{\left(\dfrac{a}{b}\right)+\left(\dfrac{l}{b}\right)}\right]} \tag{2}$$

Where:
d – sleeve diameter
l – sleeve length
$b = \dfrac{d}{2}$
$k = \dfrac{x}{l}$
Z – radial clearance

4. CORRELATION OF CARDAN SHAFTS AND SIMILARITY CRITERIA

For different geometric shapes and dimensions of coupled parts of the Cardan coupling from the production programs of several manufacturers, and based on expression (2), the values of the angle $\boldsymbol{\alpha}$ were analyzed to ensure simultaneous contact of the point at the top and the point at the root of the sleeve with a coupled part – a needle, for different values of radial clearances (Z).
An algorithm for analyzing expression (2) was written in the certain software package. According to obtained datas, the results was generated and presented on diagram, Fig. 11. The results were formed on the basis of geometric characteristics of experimentally tested Cardan couplings from the production programs of different manufacturers. Cardan shafts samples 1, 2 and 3 are of the same type of shaft, but with different dimensions and capacities, as well as samples 9 and 10, and are from the production program of manufacturer A. Samples 4-8 belong to the production program of manufacturer B but with different dimensions and capacities. Samples 11-13 also belong to manufacturer B but are of different dimensions, Fig. 8.

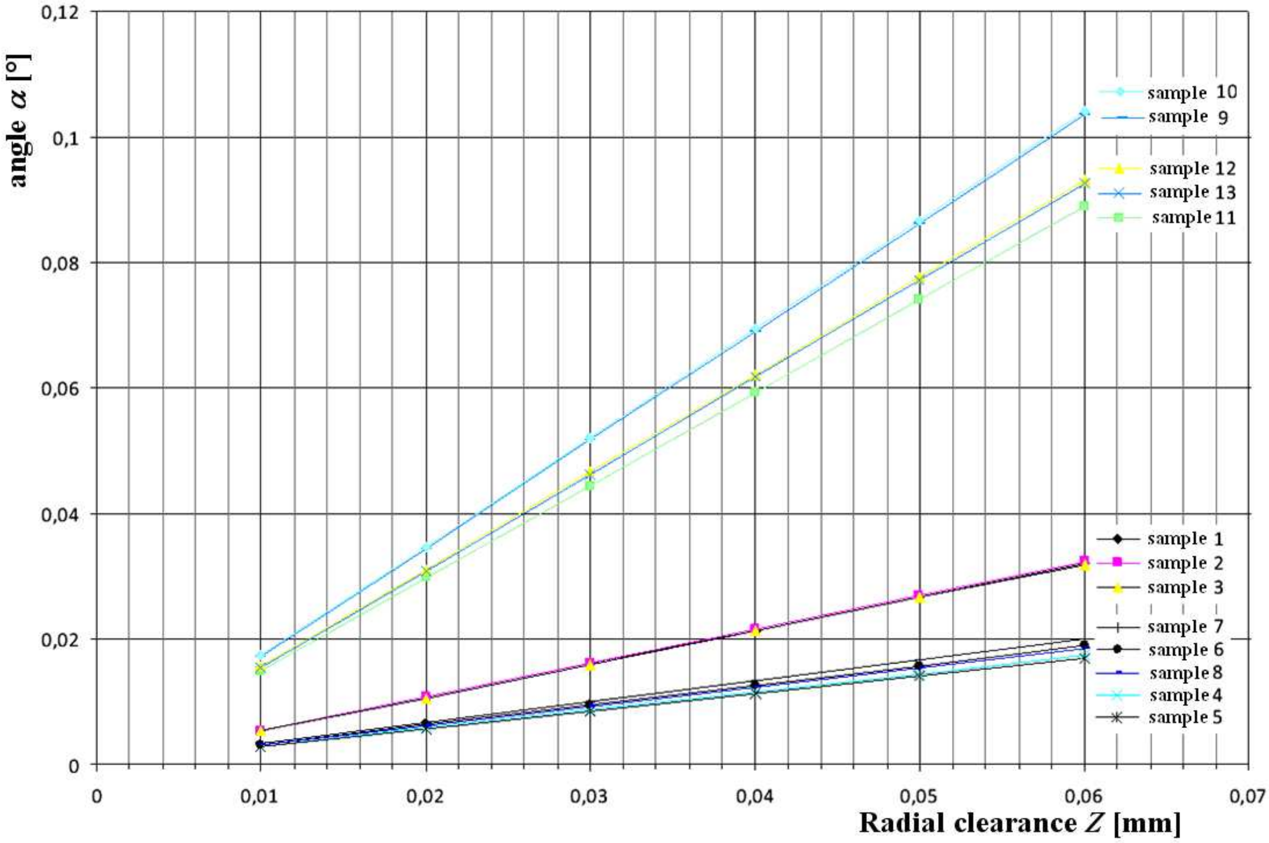


Fig. 11. Dependence of the angle α on geometric quantities (a, b and l) and radial clearance (Z) for thirteen samples.

Based on the results obtained, shown in Figure 11, the following can be concluded:

- Angle α, i.e. the angle of the cone of the contact surface of the needle bearing bushing for a certain geometry of the parts in contact (a, b and l) changes linearly with increasing radial clearance of the coupled parts;
- For manufacturer A, the function of changing the angle α depending on the radial clearance, is the same for all family members (samples 1, 2 and 3, as well as 9 and 10), diagram in Fig. 11, which shows that the considered samples certainly belong to the correctly typified families;
- The second manufacturer B has two member families (samples 4-8, as well as 11-13), in which the linear changes do not match, which indicates that the typifying process is not completely satisfied.

5. CONCLUSION

It is well recognized that manufacturers of consumer goods, as well as machineries, throughout the world are facing major new demands, including shorter product life-cycles and increasing competition. The rapid emergence of new, improved products of the new generation imposes the cheapest possible production. In response, companies are restructuring and moving away from traditional process-centred work practices in favor of concurrent engineering methods.Today's software for designing and developing product families of the same shape and material, but different dimensions and load capacity, has built-in modules for typisation and optimization. But, errors (minor or major) often occur in defining boundary conditions when developing a product family based on the parent design. Sometimes, in order to achieve as cheap production as possible and/or shorten the time in the design phase, it happens that not all similarity rules are followed. Thus, often happens that all members of the product family do not have the expected exploitation characteristics.

It is shown in this paper, through experimental and theoretical research, that some Cardan shaft is designed, so that all the rules of similarity have been complied, while the other is not, Fig. 11. Small changes of geometry on one member of family did not entirely had expected effect to the others members in family. This affects the reduction of the life in exploitation and performances from expected ones.

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REFERENCES

[1] Stamenić, Z.: Investigation of the load and service conditions influence on the Cardan coupling operational capacity, *PhD Thesis*, UDC: 621.825.6:620.17(043.3), University of Belgrade - Faculty of Mechanical Engineering, 2012,

[2] Ristivojević,M., Mitrović,R., Stamenić,Z., Mišković, Ž.: *Lecture papers from Machine Design M,* M.Sc course, University of Belgrade - Faculty of Mechanical Engineering, 2022

[3] Pahl, G., Beitz, W., Feldhusen, J., Grote, K.: Konstruktionslehre Grundlagen erfolgreicher Produktentwicklung Methoden und Anwendung, *Springer-Verlag Berlin Heidelberg*, 2007

[4] Ristivojević, M., Mitrović R., Rosić, B., Dimić,A., Mišković, Ž., Stamenić, Z., Sedak, M.: Typified Machine Parts Series Load Capacity Analysis From Aspect of Structural Strength, *Machine Design*, Vol.10 (2018) No.2, ISSN 1821-1259 pp. 31-36

[5] ISO – 10825 – 1995, Wear and damage to gear teeth

[6] Savić, Z., Puljezević, M.: Addition to the research of Cardan shaft load capability, Proceedings, P*ower transmission symposium*, Jugoslovensko društvo za motore i motorna vozila, Beograd 1976., pp. 49-69.

[7] Živković, K., Ivanović, L., Stojanović, B.: The effect of geometry on the stress distribution of cross shaft, *7th Int. Conf. IRMES*, Zlatibor 2011, 245-252

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THE INFLUENCE OF LUBRICANT VISCOSITY ON THE EFFICIENCY AND POWER LOSS OF THE WORM GEAR

Blaža STOJANOVIĆ
Lozica IVANOVIĆ

Abstract: *This paper presents an experimental analysis of the influence of lubricant viscosity on the efficiency and power loss of a worm gear transmission. The tests were performed on the open circuit power specialized testing device AT200 at the Center for testing power transmissions at the Faculty of Engineering, University of Kragujevac. In the experiment, three oils of different viscosities were used: 220 mm²/s, 460 mm²/s and 680 mm²/s. The efficiency was measured for three different values of input number of rotations: 1500 min⁻¹, 2000 min⁻¹ and 2500 min⁻¹. Output torque values range from 2.2 Nm to 6 Nm. The test results showed that the efficiency of worm gear increases with increasing input shaft speed. It was also observed that the efficiency increases with increasing oil viscosity in all test regimes. The results of the work are a reference for researching the efficiency of worm gears and engineering optimization, which is of great importance for the development of gears.*

Keywords: *Efficiency, power loss, worm gear, oil, viscosity*

1. INTRODUCTION

Mechanical transmissions are used to transfer mechanical energy from the drive machine, most often the electric motor, to the driven machine. The power transmission can also change the direction of rotation if necessary, [1].

Today, the following types of mechanical transmissions are most often used: gear drives, chain drives, friction drives, belt drives, toothed belt drives, cardan shaft, etc.

Gear transmissions have the largest application of all power transmissions. They transmit power and torque from one shaft to another when coupling gear teeth. The gear pair is the simplest form of gear transmission consisting of two gears. One gear is drive gear, while the other is driven. Torque and power are transmitted from the drive gear to the driven one, [1].

Worm gears have a wide range of applications due to numerous advantages over other types of gears. A worm gear transmission is a worm gear pair, which consists of a worm and a worm wheel. This type of transmission is a type of hyperboloid gear pair, that is, a gear pair whose axes pass each other. The angle at which the axes pass is usually 90°, but in some cases it may be smaller or larger, although this range is limited. Worm gears are rarely used as multipliers, and the reason is their relatively low value of the efficiency, which is η<0.5. The worm is smaller in diameter than the worm gear and can have one or more thread, so that it resembles a screw or a threaded spindle, which is why it is usually the drive part of the gear pair.

Depending on the number of thread, the following types of worms are distinguished [1, 2, 3]: single-start, double-start, triple-start and multi-start worms.

In general, the efficiency represents the ratio of input and output power, ie. power used for work. When it comes to worm gears, the most common problem when using them is to achieve the optimal degree of efficiency. The efficiency of the worm gear depends in part on the gear ratio and can, in certain cases, range from 0.49 for the gear ratio i = 300 to 0.9 for gear ratio i = 5. Accordingly, it is recommended that worm gears be used for lower gear ratios, [4].

As the relatively low efficiency is one of the main disadvantages of the worm gear, many researchers have worked on solving the problem, conducting experiments and analyzing the results. B.Magyar and B.Sauer [5] performed the calculation of the efficiency of the worm gear transmission ZK type, lubricated with lubricant viscosity 150 mm²/s at the output torque of 430 Nm. Their experiment resulted in a value of the efficiency in the range of 0.65÷0.74. M. Turci et.al. [6] examined the influence of axial distance, transmission ratio and type of lubricant on the degree of efficiency. They found that at an axial distance of 50 mm, gear ratio i=49 and various lubricants (polyethylene glycol (PEG), a combination of PEG + WS2 (tungsten disulfide) and synthetic oil) can achieve an efficiency in the range of 0.572 for PEG, up to 0.637 for synthetic oil.

In his work, S. H. Kim [7] examined the influence of the axial mismatch of the steering system due to vibrations when moving the vehicle, on the degree of efficiency. The results showed that in a certain short time interval, the efficiency can reach values up to 0.93. H. Sieber [8] determined the degree of utilization depending on different types of lubricants at an axial distance of 63 mm, transmission ratio i = 39 and input number of rotation 350 min^{-1}. The investigation showed a wide range of efficiency from 0.62 for PEG oil with a viscosity of 220 mm²⁄s, to 0.74 for PEG oil with a viscosity of 460 mm²⁄s.

This paper analyzes the influence of lubricant viscosity on the efficiency and power loss of the worm gearbox. The obtained results showed that the efficiency increases with the increase in the number of revolutions of the input shaft of the reducer and the increase in the viscosity of the used oils.

2. EFFICIENCY AND POWER LOSS

In practice, the efficiency of a worm gear is calculated as the ratio of output power to input power, [2,3]:

$$\eta=P_{\mathrm{out}}/P_{\mathrm{in}} \tag{1}$$

where:
P_{out} – output power, W, and
P_{in} – input power, W.

Output power can be calculated as:

$$P_{\mathrm{out}}=P_{\mathrm{in}}-P_G \tag{2}$$

where P_G – power loss, W.

Power loss of is also one of the challenges that arise in solving the problem of the degree of efficiency. H.E. Merritt [9] listed the following as one of the most common types of power loss that occur in worm gears:

− power losses, proportional to the input power, due to the friction that occurs between the worm teeth and the worm gear during their contact and

− power losses in bearings, as well as due to resistance to fluid movement, ie lubricating oil.

In the case where the worm gear is mounted on a shaft with ball bearing, then the resistance to the movement of the lubricating oil is the main influence on power loss which is a function of speed and temperature, but independent of load, [9].

The basic equation used in the calculation of power losses that occur in the worm gear, implies power losses due to resistance to sliding of the worm gear during movement (P_{Gz}), power losses that occur in bearings ($P_{G\mathrm{B}}$) and power losses at idle (P_{G0}).

Mathematically, total power losses represent the sum of all these individual values, by expression [3]:

$$P_G=P_{Gz}+P_{G\mathrm{B}}+P_{G0} \tag{3}$$

3. TESTING THE EFFICIENCY OF THE WORM GEAR TRANSMISSION

3.1. Test rig

Testing of the efficiency and power losses in the worm gear was performed on the device AT 200, which works on the principle of open power circuit, in the Center for testing power transmissions at the Faculty of Engineering, University of Kragujevac (Figure 1). Measurement of the degree of efficiency, oil temperature as well as the volume of noise that occurs in the operation of the worm gear transmission was performed on this rig. [10-12].

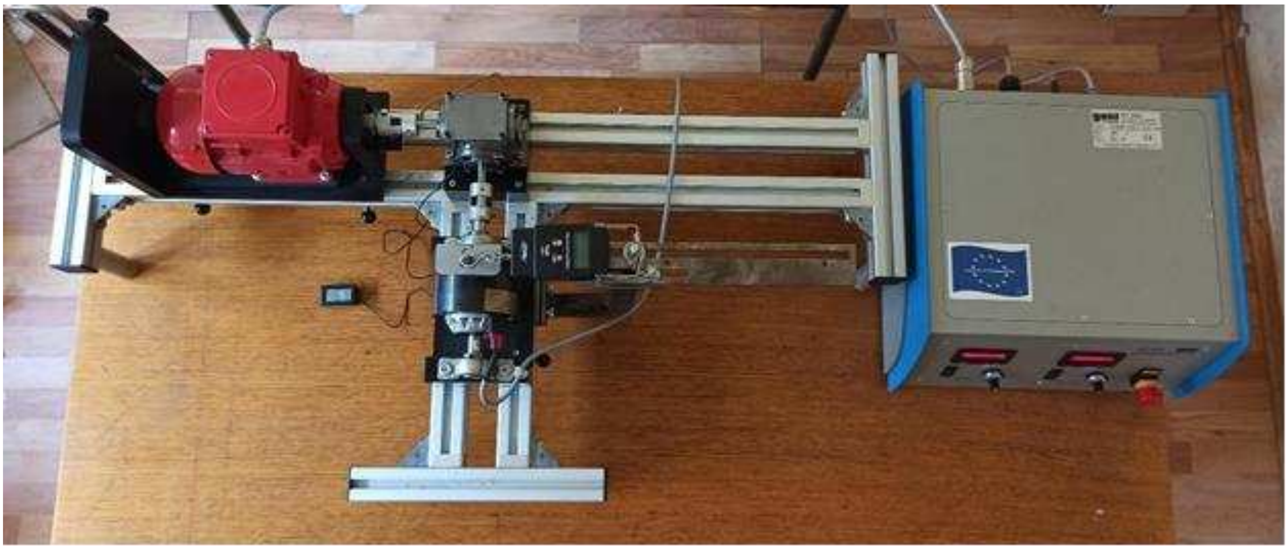

Fig.1. AT 200 device

The open power circuit consists of an electric motor that rests on the main frame over 2 bearings, so that it has no contact with the stand that is below it and can rotate around its axis. When the engine produces torque, it is subjected to a reaction moment of the same intensity but in the opposite direction. When the lever is placed in a horizontal position, and the value of the force on the dynamometer is read, the dynamometer remains locked at the given value with the help of the screw (Figure 2).

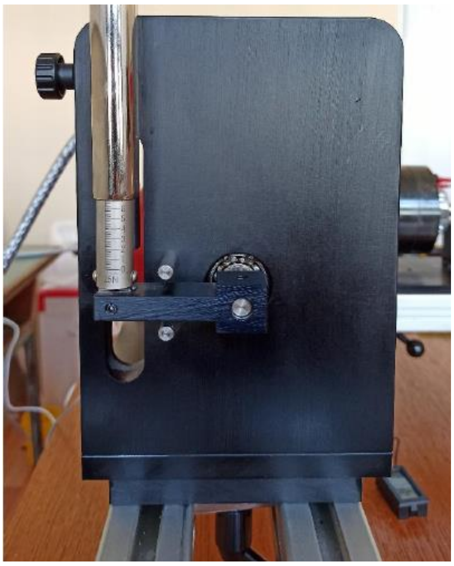

Fig. 2. Dynamometer on an electric motor

In addition to the electric motor, the device also has an electromagnetic brake with a dynamometer. On the input and output shaft there are appropriate sensors that are connected to the amplifier bridge on which the appropriate operating conditions are set.

3.2. Test conditions

The testing of efficiency on the AT 200 device was performed on a worm gear with a gear ratio i = 18, with a worm made of 42CrMo4 alloy steel and a CuSn14 tin bronze worm gear wheel. During the test, the values of the input number of rotations, the electric current on the brake (ie the corresponding output torque) were varied, and oils of different viscosities were used.
The values of the input number of rotations are 1500 min^{-1}, 2000 min^{-1} and 2500 min^{-1}, the interval of change of electric current is 0.025 A, in the range from 0.1 A to 0.2 A (corresponding to a torque of 2.2 Nm to 6 Nm depending on the test mode). The viscosities of the lubricants used in the test are 220 mm^2⁄s, 460 mm^2⁄s and 680 mm^2⁄s. The basic characteristics of the lubricants used are given in Table 1.

Table 1. Characteristics of lubricants used in the tests

Oil	Characteristics	Value	Unit
ISO VG 220	Viscosity on 40°C	220	mm2/s
	Viscosity on 100°C	18	mm2/s
	Pour point	-15	°C
	Flash point	260	°C
	Density on 15°C	896.1	kg/m3
ISO VG 460	Viscosity on 40°C	460	mm2⁄s
	Viscosity on 100°C	28	mm2⁄s
	Pour point	-12	°C
	Flash point	260	°C
	Density on 15°C	896.1	kg/m3
ISO VG 680	Viscosity on 40°C	680	mm2⁄s
	Viscosity on 100°C	40	mm2⁄s
	Pour point	-8	°C
	Flash point	300	°C
	Density on 15°C	905	kg/m3

3.3. Test plan

The test was performed in three cycles, with three series of five repetitions. Three cycles involve three different oil viscosities, three series involve three different values of the input number of rotations and five repetitions involve different values of electric current. The value of the electric current changed every hour, except for the first repetition of 0.1 A, which lasted an hour and a half, because the worm gear takes about half an hour to reach operating temperature, and the same amount is needed for the lubricant to form a hydrodynamic layer [13]. All values were measured in an interval of five minutes. After every third repetition, more precisely changes in the strength of the electric current, a break of half an hour was made in order for the device and the oil to cool down to room temperature.

4. TEST RESULTS AND DISCUSSION

Based on the measured experimental results, a program for calculating the efficiency and power loss was developed at Microsoft Excel. Figures 3-5 show the dependences of the efficiency of worm gears and torque. At the same time, three values of input number of rotations and three values of lubricant viscosity were varied.

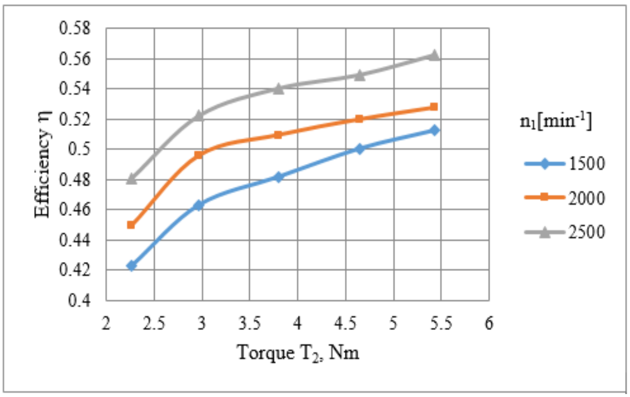

Fig. 3. Influence of number of rotations on the efficiency for oil with viscosity 220 mm²/s

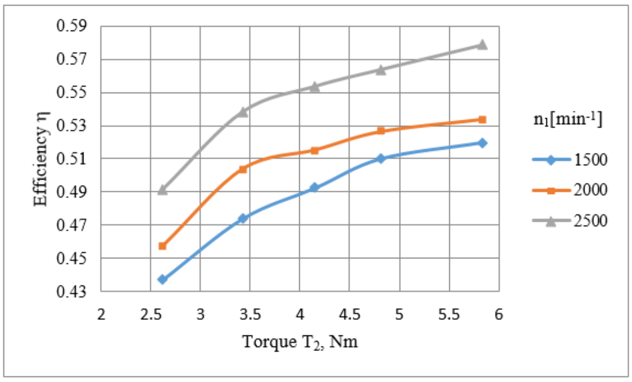

Fig. 4. Influence of number of rotations on the efficiency for oil with viscosity 460 mm²/s

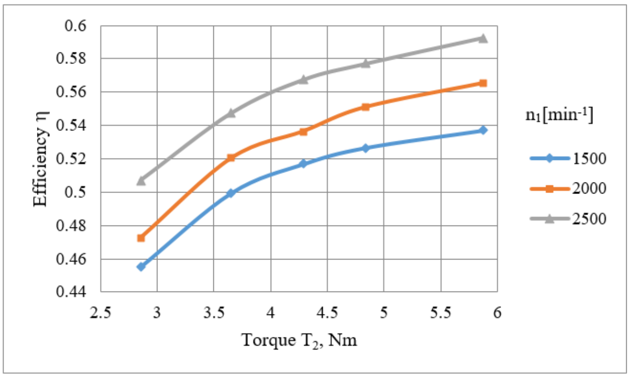

Fig. 5. Influence of number of rotations on the efficiency for oil with viscosity 680 mm²/s

In the given diagrams, it can be observed that the increases with increasing output torque and with increasing input number of rotations, for all three values of lubricant viscosity.

Figures 6-8 show the dependences of the efficiency on the number of rotations of the input shaft for all three values of the viscosity of the lubricant.

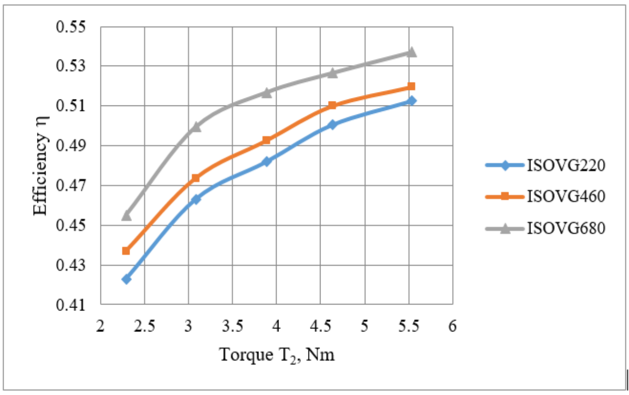

Fig. 6. Influence of lubricant viscosity on the efficiency for number of rotations 1500 min⁻¹

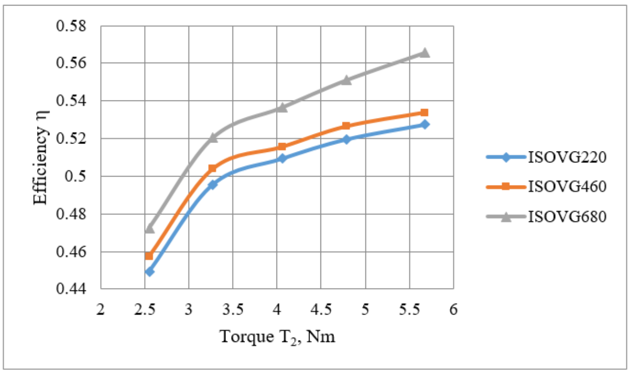

Fig. 7. Influence of lubricant viscosity on the efficiency for number of rotations 2000 min⁻¹

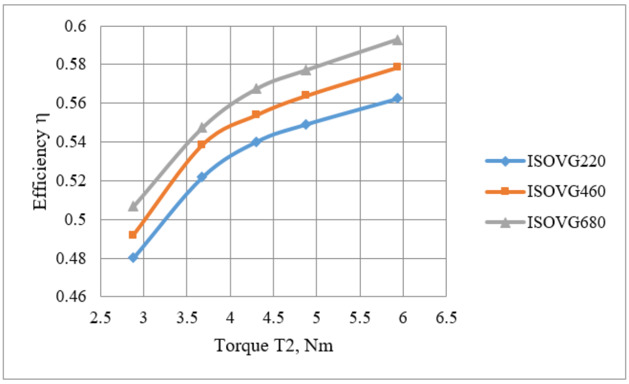

Fig. 8. Influence of lubricant viscosity on the efficiency for number of rotations 2500 min⁻¹

The diagrams show that the efficiency increases with increasing lubricant viscosity in all test modes, ie for different input shaft number of rotations. The maximum values of the efficiency are obtained by using oil with a viscosity of 680 mm²/s and are 0.53 ÷ 0.59.

The influence of lubricant viscosity on the degree of power loss P_G/P_1 is shown in Figures 9-11. The diagrams show that the lowest losses occur when using oils of the highest viscosity and at the highest output torques.

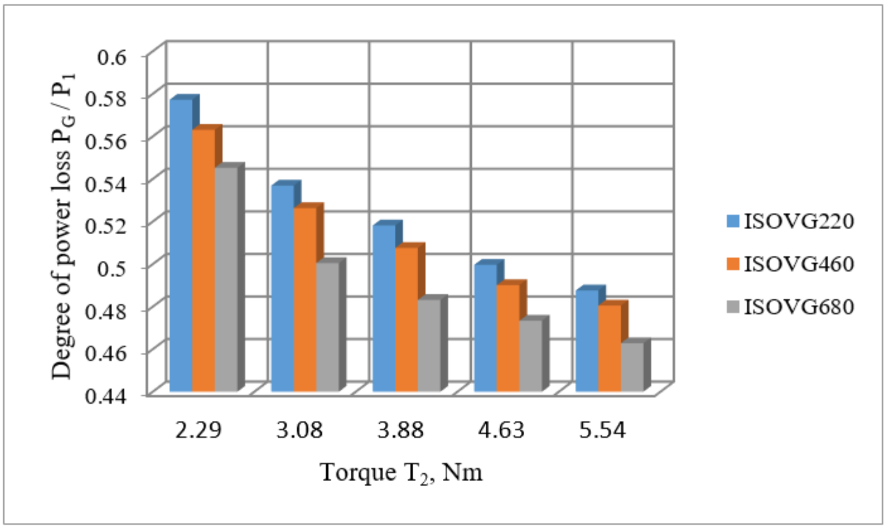

Fig. 9. Influence of lubricant viscosity on the degree of power loss for number of rotations 1500 min^{-1}

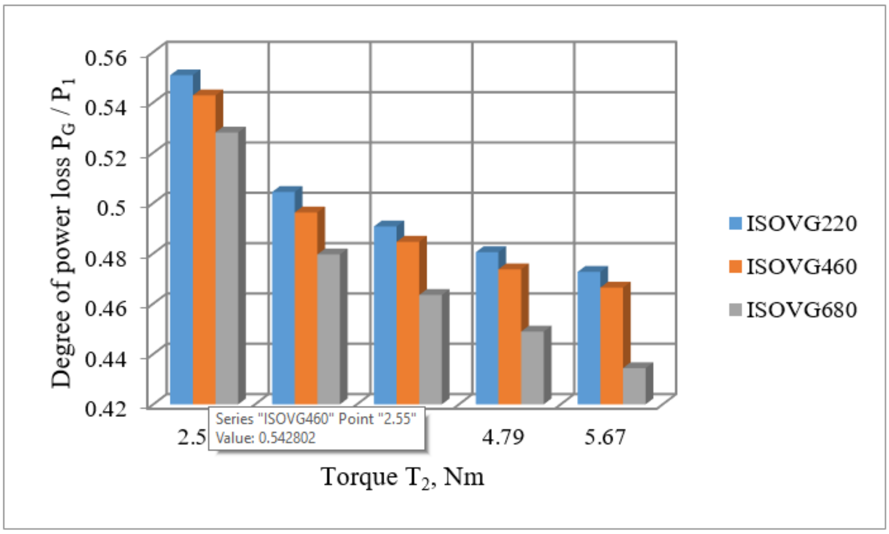

Fig.10. Influence of lubricant viscosity on the degree of power loss for number of rotations 2000 min^{-1}

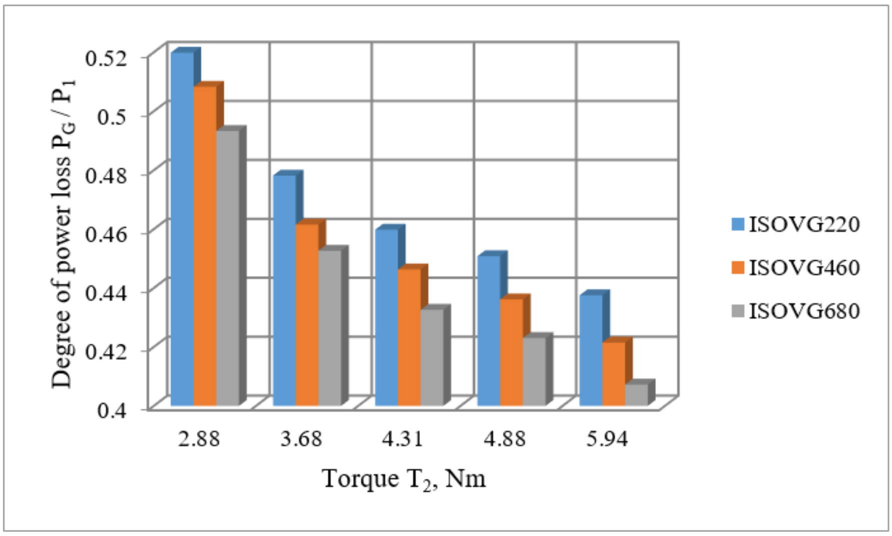

Fig. 11. Influence of lubricant viscosity on the degree of power loss for number of rotations 2500 min^{-1}

5. CONCLUSIONS

At a time when the value of electricity is growing enormously and when there is a lack of all forms of energy, the analysis of the efficiency and power loss of the worm gear has become even more important. Based on the theoretical analysis and realized experimental tests, the following conclusions can be drawn.

- The value of the efficiency is influenced by the viscosity of the oils used, the input shaft number of rotations as well as the value of the output torque.
- As the number of revolutions of the input shaft increases, the efficiency of the worm gear increases.
- With the increase of the output torque, the efficiency of the worm gear also increases.
- From all the considered parameters, the viscosity of the lubricant has the greatest influence on the efficiency of worm gears. As the viscosity of the lubricant increases, the efficiency increases.
- The highest values of the efficiency occur when using oils with a viscosity of 680 mm2/s and range from 0.53 to 0.59.
- The lowest power losses occur at the highest number of rotations and with the use of the highest viscosity oil.

The results of the research provide guidelines for increasing the efficiency of worm gears, which is of great importance for the field of mechanical transmissions.

REFERENCES

[1] Stojanović, B., Blagojević, M.,: *Mechanical transmission* 1, Faculty of Engineering University of Kragujevac, ISBN 978-86-6335-083-0, 2021.

[2] Nikolić, V.,: *Machine elements, theory, calculation, examples*, Faculty of Mechanical Engineering, Prizma, Kragujevac, ISBN 86-80581-62-3, 2004.

[3] Miltenović, V., Ognjanović, M.,: Machine elements 2, Elements for power transmission, Faculty of Mechanical Engineering, Niš, 1995.

[4] www.machinedesign.com/motors-drives/article/21834720/gear-efficiency-key-to-lower-drive-cost, Accessed on: 2022-04-18.

[5] Magyar, B., Sauer, B.,: Calculation of the Efficiency of Worm Gear Drives, *Power Transmission Engineering*, pp. 52-56, 2015

[6] Turci, M., Ferramola, E., Bisanti, F., Giacomozzi, G.,: Worm Gear Efficiency Estimation and Optimization, *Gear Technology*, Vol. 33, No.4, pp.46-53, 2016.

[7] Kim, S. H.,: Worm gear efficiency model considering misalignment in electric power steering systems, *Mechanical Sciences,* Vol. 9, No.1 pp.201-210., 2018.

[8] Siebert, H.,: Worm Gears - Higher Energy Efficiency and Less Strain on Resources, *Gear Technology*, Vol. 5, pp.26-30, 2011.

[9] Merritt, E. H.,: Worm Gear Performance, *Proceedings of the Institution of Mechanical Engineers*, 129(1):127, 1935.

[10] GUNT: Experiment Instructions, AT 200 Apparatus for Determination of Gear Efficiency, 2011.

[11] Radosavljević, S., Stojanović, B., Skulić, A.,: Determination of power losses in worm gear reducer, *IOP Conf. Series: Materials Science and Engineering* 393(1), 012050, 2018.

[12] Skulić, A., Stojanovic, B., Radosavljević, S., Velickovic, S.,: Experimental determination of worm gearing efficiency., *Applied engineering letters*. 4(4),115 – 119, 2019.

[13] Rac A: Lubricants and lubrication machines, Faculty of Mechanical Engineering, Belgrade, ISBN 978-86-7083-595-5, 2007.

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DIGITAL TRANSFORMATIONS IN MECHANICAL ENGINEERING, TRENDS IN EDUCATION IN THE FIELD OF MACHINE ELEMENTS AND SYSTEMS

Milan TICA
Tihomir MAČKIĆ

Abstract: *In the changes that come with Industry 4.0, the education of engineers has a very important role. The general trend is to transform existing products into mechatronic and smart products. Within the digital transformations in mechanical engineering, the use of digital technologies, sensors and actuators as other elements of smart products is significant. For a mechanical engineer, it is necessary that, in addition to a good knowledge of conventional mechanical elements and systems studied so far, such as joining elements (screwed, riveted, welded joints) or elements for mechanical transmissions (gears, shafts, bearings), has a good knowledge of the basics of digital technologies, sensors and actuators, as well as other elements built into modern products.*

Keywords: *Industry 4.0; digital transformations; education; machine elements*

1. INTRODUCTION

Industry 4.0 has a huge impact on the entire social system. The speed, scope and impact of the changes it brings, have an exponential trend. The biggest impact is related to industry and industrial development. Full digitalization and automation is expected in the production, i.e. networking of smart digital devices with final products, machines, tools, robots and people. For the realization of such complex tasks, it is necessary to have adequate human resources. In the changes brought by Industry 4.0, engineering of smart products and services, i.e. education of engineer development, has a very important role. It forms new trends in the education of development engineers. Engineers are expected to be comprehensively educated and possess interdisciplinary knowledge and skills. Therefore, some adjustment is needed in the education of engineers. Content, education and courses within basic subjects are especially important. One of such course is Machine Elements.

2. DIGITAL TRANSFORMATIONS IN MECHANICAL ENGINEERING

The concept of Industry 4.0 began in 2011, based on a "smart factory" in which all processes are automated from communications to the production process in order to achieve maximum profit.

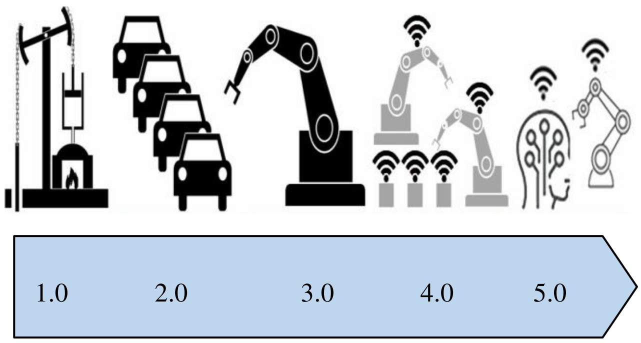

Fig.1. Industrial revolutions

The structure of employees in factories is changing. Employees are required to have new knowledge in the field of informatics. The concept of Industry 4.0 is especially good for manufacturing companies that produce large quantities of products, which can be different, personalized, but use the same type of work technology. High-volume production very easily becomes mass production, and at the same time the final product is increasingly influenced by the customers' requirements.
The Industry 4.0 concept encompasses digitization, robotics, communication, cyber-physical systems, and the Internet of Things. Within Industry 4.0, completely new production systems have been created that can meet the demands of today's market. One of the most important requirements is a personalized product according to the customer's wishes at a low price. This product should be

delivered to the customer in a relatively short time. This concept includes monitoring of products during production, during operation, as well as monitoring of servicing. There are also some objections to the concept of Industry 4.0 that dehumanization is carried out within it. Due to the large increase of using the robots in production, there is a fear that there will be a decline in employment. Figure 3 shows the ratio of the number of robots per 10.000 employees in correlation with the number of unemployed for some countries.

Fig.2. Industry 4.0

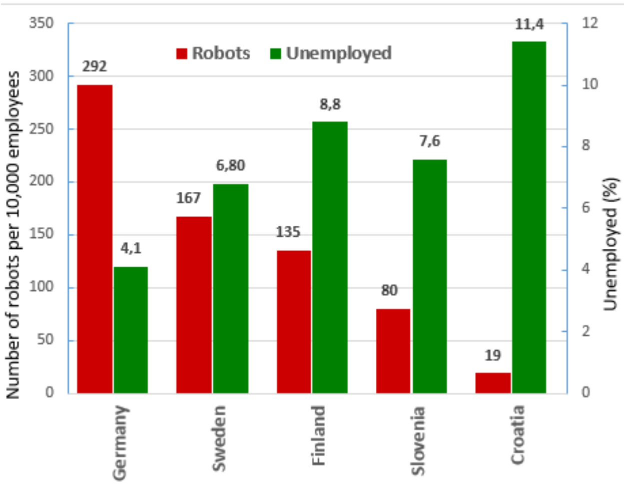

Fig. 3. Number of robots per 10000 employees in correlation with the number of unemployed for some countries [6]

Reality shows that new jobs are being created for man, as well as new, more creative jobs. Recently, we are also talking about Industry 5.0, whose focus is on the interaction between humans and machines, i.e. between humans and robots. This human-robot interaction combines human creativity and skill with robot speed, productivity and precision to create new commercial and social values.

For industry 5.0, one can say that it is more humane, figuratively speaking, industry 5.0 returns "human touch" or people to production. The concept of Industry 5.0 is more suitable for medium and small enterprises. In small and medium-sized enterprises, full automation is not cost-effective, and market demands for specific products at the request of customers are increasing. Likewise, large manufacturing companies have technological operations that are not cost-effective to automate, where mutual cooperation between cobots and workers is more cost-effective. Cooperation between cobots and humans is also possible in the field of plant maintenance.

Fig.4. Industry 5.0

Technically and developmentally, Industry 5.0 is not a continuation of Industry 4.0, it cannot be considered a new, so-called fifth industrial revolution, but it is an improvement of Industry 4.0 within it is possible to adapt the product to each individual customer. This adaptation requires the creativity and skills of humans, and the speed and precision of cobots.

3. EDUCATION OF MECHANICAL ENGINEERS

Accelerated technical and technological development of the industry requires even faster development of education. It all starts with education, because education is not a consequence but a cause. Education is one of the most important resources in the state and society. We live in a time of rapid change and the accelerated development of science. Total knowledge is rapidly increasing. It is estimated that the total knowledge of mankind is now doubling in one year. It used to last for hundreds of years, then for tens, then for several years, and today the total knowledge has doubled in one year (Figure 5). New solutions must be found in education, the former classical and inert approach in education, which was limited by the duration of education, needs to be replaced by a new approach, which implies constant upgrades and improvements. Basic knowledge needs to be upgraded with new ones. Lifelong learning becomes an imperative of success for the individual and society as a whole. Every individual in education needs continuous education and mastery of new knowledge. Modernization of teaching content, constant education of teachers, introduction of new teaching methods, integration of theoretical and practical teaching, participation in projects, teamwork, are just some of the elements that should lead to improving the educational process.

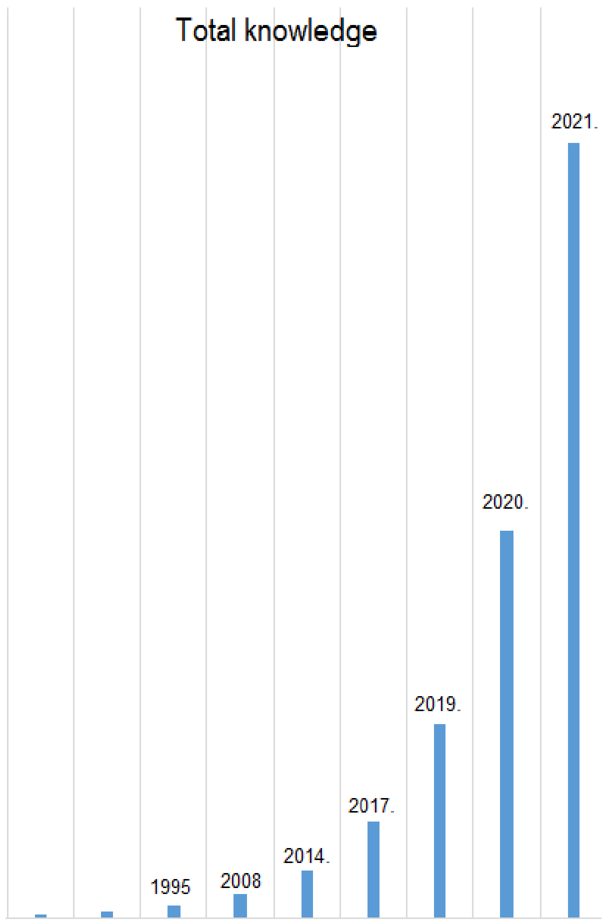

Fig.5. Display of ever shorter time between each doubling of total knowledge

In accordance with the transformations of mechanical engineering, the transformation of the education of mechanical engineers is inevitable. New technologies are an integral part of the education of mechanical engineers. We are witnessing that technologies are changing rapidly, and their constant monitoring is needed. Today's mechanical engineers, in addition to basic knowledge, need to have more knowledge and skills about new technologies. Mechanical engineers need to master the knowledge and be trained to use adequate methods, models and IT tools to solve problems in a constantly changing inter-disciplinary environment. Therefore, mechanical engineers must be prepared for lifelong learning. Mechanical engineering as a science is rapidly developing, and this requires constant monitoring of new trends and, consequently, changes in the education of mechanical engineers. In that sense, development engineers should also be the initiators of the transformation of education in this field. Faculties should modify curricula, in which they should incorporate new trends, so that graduates have competencies and be able to work with advanced technologies. It is understood that the competence is acquired at the faculty and later upgraded in practice.

3.1. Trends in education in the field of machine elements and systems

Starting from the definition of a machine element, as a machine part or assembly that performs an elementary function within a machine system, it can be concluded that the number and types of machine elements have expanded with the advent of new technologies and their application.

Taking into account the fact that machine systems and their components, assemblies, subassemblies and machine elements are being modernized, there is a need to modernize the study of machine elements and systems. Robots and cobots are the latest generation of machine systems. Their production and application is growing significantly. The general trend is to transform existing products into mechatronic and smart products. Sensors and actuators have become an integral part of machine systems today and as such represent a very important group of machine elements.

Figure 6 shows the car's sensors. The positions in fig. 6 indicate the following sensors: 1- white line tracking sensor (controls the stay in the traffic lane), 2- night driving sensors, 3- front „CCD“ camera, 4 - airbag actuators, 5- „ASCD“ , 6- pedestrian detection sensor, 7- driver fatigue sensor, 8- laser sensor for detecting objects on the front, 9- „IR“ pedestrian detection sensor, 10- parking sensors, 11- tire pressure sensor, 12 – rear camera control unit, 13- rear „CCD“ camera, 14 – air curtain sensor, 15- blind spot sensor, 16- object detection sensor on the front, 17- central control unit, 18- object detection sensor on the back, 19- speed sensor, 20- tire pressure sensor, 21- auto-brake sensor, 22- side airbag sensor, 23- adaptive cruise control, 24- steering wheel position (angle) sensor, 25 – automatic braking actuator, 26- wheel speed sensor.

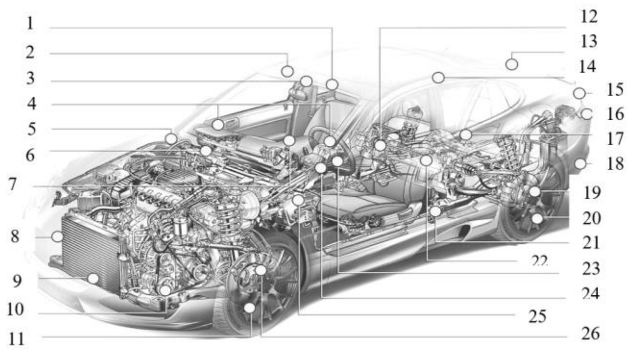

Fig.6. Sensors and actuators in the car [5]

Such trends require good knowledge of mechanical engineers in the field of sensors and actuators, as indispensable elements in today's products. Today, it is very difficult to find a machine system that does not have sensors and actuators. For a mechanical engineer, it is necessary that, in addition to a good knowledge of conventional machine elements and systems studied so far, such as joining elements (screwed, riveted, welded joints) or elements for mechanical transmissions (gears, shafts, bearings), has a good knowledge of the basics of

digital technologies, sensors and actuators, as well as other elements built into modern products.
In accordance with the changes brought by Industry 4.0, the education of mechanical engineers of all specialties is also changing. The education of constructors and development engineers is especially changing. Instead of the previous classic products, designers today need to be able to construct complex mechatronic systems and smart products. An integral part of the education of constructors should be modern technologies, which are rapidly changing and improving, and there is a need for constant adaptation in education.

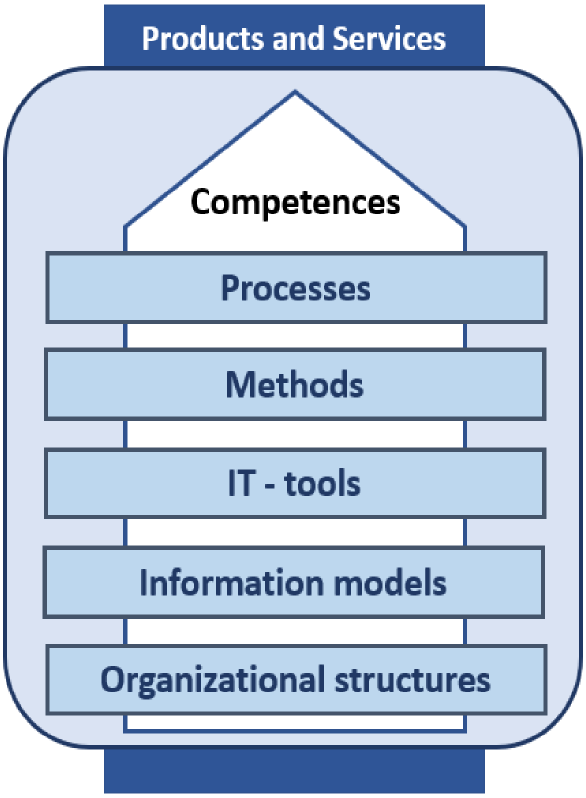

Fig.7. Components of the holistic engineering *[2], [6]*

Today, mechanical engineers need to have more knowledge and skills, especially about new technologies. In addition to basic knowledge, they need to possess specific skills and competencies related to innovation. The development of new machine, i.e. mechatronic (smart) systems is most often based on innovations. Designers today need to analyze a lot of data and take into account many influential factors, and in accordance with the available resources to optimize and come up with an optimal solution in a short time. Late solutions are not good solutions, even if the whole job was done without a mistake. Nowadays, we need mechanical engineers and constructors who are able to cope with new challenges. In addition to classical knowledge in the field of mechanics and machine elements, they need to have knowledge of information technology in order to be able to solve problems in a high-tech interdisciplinary environment, which is constantly changing. Therefore, mechanical engineers must be prepared for lifelong learning.

3.2. Analysis of study programs of the subject Machine Elements

Within this research, the study programs of the subject Machine Elements in several countries were analyzed. The analysis shows the difference in the hours of lectures and exercises, the number of ECTS credits, as well as the content of the subject.
Table 1 presents comparative data for the subject Machine Elements at domestic faculties.

Table 1. Machine elements at domestic faculties

University	Course title	mandatory /elective	Number of semesters	Hours per week L+E	ECTS
Banja Luka	Machine elements 1 Machine elements 2	m	2 (III and IV)	3+2	6
Niš	Machine elements 1 Machine elements 2	m	2 (III and IV)	2+3	7
I. Sarajevo	Machine elements 1 Machine elements 2	m	2 (III and IV)	3+2	6
Beograd	Machine elements 1 Machine elements 2	m	2 (III and IV)	3+2	6
Podgorica	Machine elements 1 Machine elements 2	m	2 (III and IV)	3+2	6
Novi Sad	Machine elements	m	1 (III)	4+4	8
Kragujevac	Machine elements	m	1 (III)	2+3	7

There is a noticeable discrepancy between the number of hours during one academic year and the number of ECTS credits from the subject Machine Elements at domestic faculties. Figure 8 shows the representation of teaching hours and ECTS credits at domestic faculties. It can be seen that the curricula from mechanical elements, at the Faculty of Engineering of Kragujevac and the Faculty of Technical Sciences of Novi Sad, are concentrated only on one semester and have a larger number of ECTS credits and a larger number of teaching hours per semester. In addition, within the teaching module Construction Engineering, at the Faculty of Engineering in Kragujevac, the subjects Mechanical Elements 2 are studied.
At other domestic faculties, teaching in the field of mechanical elements is divided into Mechanical Elements 1 and Mechanical Elements 2. At the Mechanical Faculty of Banja Luka and the Faculty of Mechanical Engineering of East Sarajevo, modifications were made to the Mechanical Elements 2 course program, within which sensors and actuators are studied.

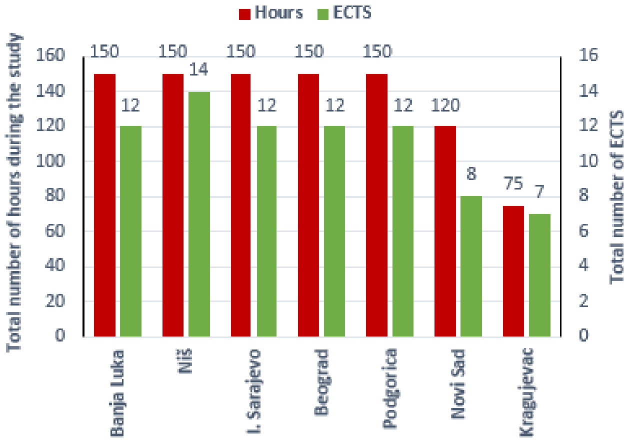

Fig.8. Representation of teaching hours and ECTS credits at domestic faculties

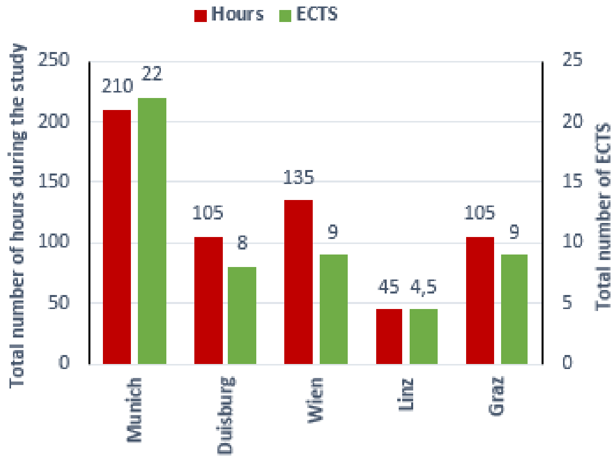

Fig.9. Representation of teaching hours and ECTS credits at foreign faculties

In order to understand the quality and structure of teaching at domestic faculties, an analysis of teaching content and classes in the field of studying machine elements at foreign faculties in the area was performed. Table 2 presents comparative data for the subject Machine Elements at foreign faculties.

Table 2. Machine elements at foreign faculties

University	Course title	mandatory /elective	Number of semesters	Hours per week L+E	ECTS
Munich	Machine Elements 1 Machine elements 2 Machine elements - production, application	m	3 (III, IV and V)	3+2 3+2 2+2	6 9 7
Duisburg	Machine Elements 1 Machine elements 2	m	2 (III and IV)	2+2 2+1	5 3
Wien	Machine Elements 1 Machine elements 2 Machine elements 3	m	3 (III, IV and V)	2+1	3
Linz	Machine elements	m	1 (III)	2+1	4,5
Graz	Machine Elements 1 Machine elements 2	m	2 (III and IV)	2+2 2+1	5 4

Several faculties from Austria and Germany were selected, due to the high level of industrial development in those countries. Figure 9 shows the representation of teaching hours and ECTS credits at foreign faculties. Significant diversity is evident, when the number of teaching hours and the number of ECTS credits are considered.

The study of machine elements is significantly represented at the TUM School of Engineering and Design at Technical University of Munich. It is also known that this university has a large number of laboratories for testing machine elements. Therefore, at this university, there are a very large number of classes and ECTS credits. In Munich, the study and application of machine elements in modern products are studied, with reference to the use of sensors and actuators within the subject Machine elements - production, application.

The Technical University of Vienna teaches mechanical elements for three semesters. However, a significantly small number of classes in each semester is evident. At the master's study, special machine elements, transmissions in the aviation industry and ways of controlling special machine elements with the help of sensors are studied.

At other foreign faculties in the area, a significantly smaller number of classes is noticeable, as well as a small number of ECTS credits. The curricula are mainly based on the study of conventional machine elements.

4. CONCLUSION

Industry 4.0 has led to major changes in all spheres of society, especially in technology. The technological leap is so pronounced and is on a steady rise. New technologies are removing the boundaries between specially studied fields of science (mechanical engineering, electrical engineering, biology, medicine, etc.). Changes are happening very fast. Education must accompany these changes. Universities need to update their curricula and develop programs that should provide students with the knowledge and skills needed to work effectively in a new "smart" environment. The main activity in the era of the Fourth Industrial Revolution was the development of smart products and services. The education of mechanical engineers should cover multidisciplinary areas which, in addition to mechanical engineering, must include electronics, software engineering and new advanced technologies. The general trend is to transform existing products into mechatronic and smart products. Within the digital transformations in mechanical engineering, the use of digital technologies, sensors and actuators as other elements of smart products is significant. For a mechanical engineer, it is necessary that, in addition to a good knowledge of conventional mechanical elements and systems studied so far, such as joining elements (screwed, riveted, welded joints) or elements for mechanical transmissions (gears, shafts, bearings), has a good knowledge of the basics of digital technologies, sensors and actuators, as well as other elements built into modern products. In line with new trends, existing curricula need to be modified to educate engineers for the future.

REFERENCES

[1] Abramovici, M.: *Engineering smarter Produkte und Services Plattform Industrie 4.0*. STUDIE. Deutsche Akademie der Technikwissenschaften. München, 2018.

[2] V.Miltenović, Z. Nikolić, M. Milojković, S. Perić: *Systematic approach to the education in the field of smart products and services engineering,* FACTA UNIVERSITATIS Series: Automatic Control and Robotics Vol. 20, No 2, 2021, pp. 1 - 14

[3] V. Miltenović, M. Tica, B. Marković: *Konstrukcioni elementi u mašinogradnji 2*. Istočno Sarajevo, 2020

[4] Miltenović, V., Antić. D.: *Smart Products and Services Engineering (in Serbian)*, University of Niš, Niš, Serbia, 2020. p. 202.

[5] Stokanić M.: *Sigurnosni konstrukcioni elementi u mašinogradnji*, Završni rad, 2019., Banja Luka

[6] G. Nikolić: *Is industry 5.0 responding to industry 4.0 or its resume?,* Polytechnic & design Vol. 6, No. 2, DOI: 10.19279/TVZ.PD.2017-6-2-01, 2018.

[7] https://www.elmedint.com/vesti/61-industrija-40/, Accessed on: 2022-04-24

[8] http://mf.unibl.org/prvi-ciklus-studija-2016/druga-godina-2016/, Accessed on: 2022-04-24

[9] http://www2.masfak.ni.ac.rs/sitegenius/topic.php?id=1509, Accessed on: 2022-04-24

[10] https://www.maf.ues.rs.ba/masinstvo/, Accessed on: 2022-04-24

[11] https://www.mas.bg.ac.rs/studije/oas/start, Accessed on: 2022-04-24

[12] https://www.ucg.ac.me/studprog/5/1/1/2021-masinstvo-2019, Accessed on: 2022-04-24

[13] http://ftn.uns.ac.rs/56144026/mehanizacija-i-konstrukciono-masinstvo, Accessed on: 2022-04-24

[14] http://www.mfkg.rs/sr/studije/oas/oas-studijski-programi/masinsko-inzenjerstvo, Accessed on: 2022-04-24

[15] https://www.mec.ed.tum.de/fzg/startseite/, Accessed on: 2022-04-20

[16] https://www.ikp.tuwien.ac.at/machine_elements_and_transmissions_for_aviation/EN/, Accessed on: 2022-04-20

[17] https://www.uni-due.de/kkm/lehre.shtml , Accessed on: 2022-04-20

[18] https://www.jku.at/en/degree-programs/types-of-degree-programs/bachelors-and-diploma-degree-programs/ba-in-mechanical-engineering/ , Accessed on: 2022-04-20

[19] https://www.tugraz.at/en/studying-and-teaching/degree-and-certificate-programmes/bachelors-degree-programmes/mechanical-engineering/ , Accessed on: 2022-04-20

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SMART PRODUCTS – STATE OF THE ART

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Abstract: *Smart products represent the aspect of intelligent products related to the application of the Industry 4.0 model in production, i.e. the technological systems where they are produced. It can be concluded that the term 'smart product' has the same content and meaning as the 'intelligent product'. However, these products nowadays obtain a new dimension that blurs the line between the product (hardware) and the service related to it or derived from it (intelligence), so now the user has new opportunities. For more than two decades, these products have been the subject of research around the world, so this paper aims to provide an overview of different approaches regarding the aspects of definition, development, design and application. In addition, an analysis of intelligent products research and development in the Republic of Serbia is given*

Keywords: *smart products; research; development; application*

1. INTRODUCTION

Smart products are transforming the manufacturing industry, and, vice versa, creating a new framework for the application of innovations in manufacturing, starting with product development [1]. Today, there is no universal definition of a 'smart product', but this term was first used in the context of a product lifecycle information system [17], and intelligent manufacturing and supply chain [15,16]. Hence, it started with the term "intelligent products", and nowadays the established term is "smart products".

This is the same concept and model of the product. The first systematization of terms and definitions of intelligent products is given in [11]. Today, one of the definitions of an intelligent product can be our contribution to these considerations - the location of our business is the place of use of our product, from where the customer, consciously or unconsciously, generates and sends information about its behaviour!

On the other hand, if a detailed analysis of references for the last two decades is performed, it can be concluded that researchers in this field have focused their research on: (i) defining concepts and models of intelligent products, (ii) application of information technology to support intelligent products, and (iii) technological systems and their concepts as a support for the development, manufacturing and application of intelligent products.

Regarding the concept and model of intelligent products, their taxonomy is presented in [3], and the levels and their analysis in [4,11], design principles in [5,9], research of customer satisfaction with intelligent products in [24], and intelligent design of these products in [30,33]. It is important to note that AI tools and techniques, including deep machine learning (ML), have been recently used increasingly.

Information technologies form the basis of intelligent products, and the most common approaches include: the use of PLM by IoT [2], digital modelling of intelligent products [13], smart engineering as a basis for intelligent products [7,8,14], big data analysis [26,27], and machine learning and its application in intelligent products [28,29,32].

At the level of technological systems, intelligent products have been researched from the following aspects: business model of the organization [1,7,10,31], use of agent technology in manufacturing management [6,12,21], supply and delivery chain management [15,19], production planning and management (MES) [16,18], maintenance planning and management [17], product life [22], and smart manufacturing [23].

This paper has several sections: (a) analysis of the definition of intelligent products, (b) structure of intelligent products and its elements, (c) the state of development of intelligent products, (d) design of intelligent products, and (e) levels of intelligent products and selected examples.

The aim of this paper is to provide an overview of the state of research and development of intelligent products from different angles, in order to gain a comprehensive insight into this area, especially from the aspect of the future development and application of the Industry 4.0 model.

2. BASIC DEFINITIONS OF INTELLIGENT PRODUCTS

In [18], the first integral definition of an intelligent product, which has physical and information representation, is given. The connection between the physical product and its representation is based on information obtained by means of a tag (QR code) and a reader (RFID). Thus, the intelligent product acquires the following characteristics: (i) has a unique identification, (ii) has the ability to communicate effectively with its environment, (iii) generates and stores information about itself, (iv) uses language to display its characteristics, product requirements, usage history, etc., and (v) is able to generate or make relevant decisions about its present and future status.

According to the previous definition, [16] two levels of product intelligence are given: (i) information (levels i-iii), and (ii) user (decision making), which covers all five levels. This is a generic classification of intelligence, and in it, for example, information can be generated and used for the procurement of raw materials [15], as well as its manufacturing [16], using RFID technology.

The second definition is oriented towards intelligent products coming from SMEs [19], which are part of the supply chain. In order to extend the connections of an intelligent product outside the SME, it should have the following characteristics: (a) global identification code (during its lifetime), (b) connection to information sources outside the SME, and (c) the ability to communicate with the users, including proactive activities as well. This definition is fully covered by the characteristics of an intelligent product according to [16].

The following definition [20] is more comprehensive than the previous two, and refers to intelligent products and systems, which have the following characteristics: (a) they continuously monitor their condition and communication with the environment, (b) make decisions about working conditions, (c) manage the optimal performance, and (d) actively communicate with the environment (the user, other products and systems). From these characteristics, it could be concluded that these products have the necessary computer support (hardware and software).

In [24], the relationships between product intelligence and its consumer perception were investigated. This research provided an intelligent product model with six dimensions: autonomy, ability to learn, reactivity, ability to cooperate, human-like interaction, and personality. The last two dimensions are especially relevant to the users of these products.

A summary analysis of this point shows that intelligent products have completely new dimensions compared to classic products with the same purpose, which means that their design and manufacturing require completely new engineering knowledge and their symbiosis at all stages of the product service life.

3. BASIC STRUCTURE OF INTELLIGENT PRODUCTS

In order to be able to research intelligent products from different aspects, the following classification model is presented [3-5,11]. The model was developed through three dimensions: the level of intelligence, its location and its content, Table 1.

Table 1.Dimensions of intelligent product characteristics

<table>
<tr><th>Level of intelligence</th><th>Location of intelligence</th><th>Object of intelligence</th></tr>
<tr><td>Information manipulation</td><td rowspan="2">On the Network</td><td>Narrow information (product)</td></tr>
<tr><td>Problem reporting</td><td rowspan="2">Wider information (system)</td></tr>
<tr><td>Decision making</td><td>On the product</td></tr>
</table>

Product intelligence is monitored through three levels: (a) manipulation of information means that the product manages information about itself, assisted by sensors, RFID readers or other techniques. When this information is extended with the production and supply chain information (to the user), then the full management of this segment of an intelligent product is established; (b) informing the environment (users) about the problem in the intelligent product; and (c) making decisions about themselves, without external interventions [9].

The second dimension is intelligent content and its location: (a) online (server or cloud), where agent technology is used as an interface for its intelligence [6,12,21], and (b) intelligence on the product with the integrated Smart Device (SD) [3,8,9], with hardware/software support to fully realize the intelligent function of the product.

Engineering products have complex structures, where their components can be entities for themselves (such as a roller bearing), so it is important to define the third dimension of an intelligent product – an object (machine, assembly, subassembly, part). In modern products, which have their own intelligent processor (PLC), it is sufficient, for example, that a part has an identifier, with the basic functions of collecting information, which is processed elsewhere. However, in this case, there must exist a special communication interface for unique access to information at all levels [8,22]. Thus, from the object aspect, we have: (a) pieces of information managed by the product which are related directly to themselves (notifications and decisions), and (b) pieces of information related to the entire system, including components (for example, intelligent spare parts management, when automatic ordering is performed once that stock level is reached).

The concept of intelligent products presented above requires the application of advanced technologies for their upgrade, for generating, storing, processing and transfer of information.
Smart products and their components (parts), but also raw materials [23] used for products in smart manufacturing, are marked and monitored with electronic devices, as shown in Figure 1 [23].

The basic characteristics of these devices are also given in the same figure, which represents a framework for managing intelligent products, according to the characteristics shown in Table 1. Reuse is a property of products / parts / materials that can be recycled or reused in the system. It can be debated whether reuse should be considered as a part of energy / efficiency savings or smart products / parts / materials.

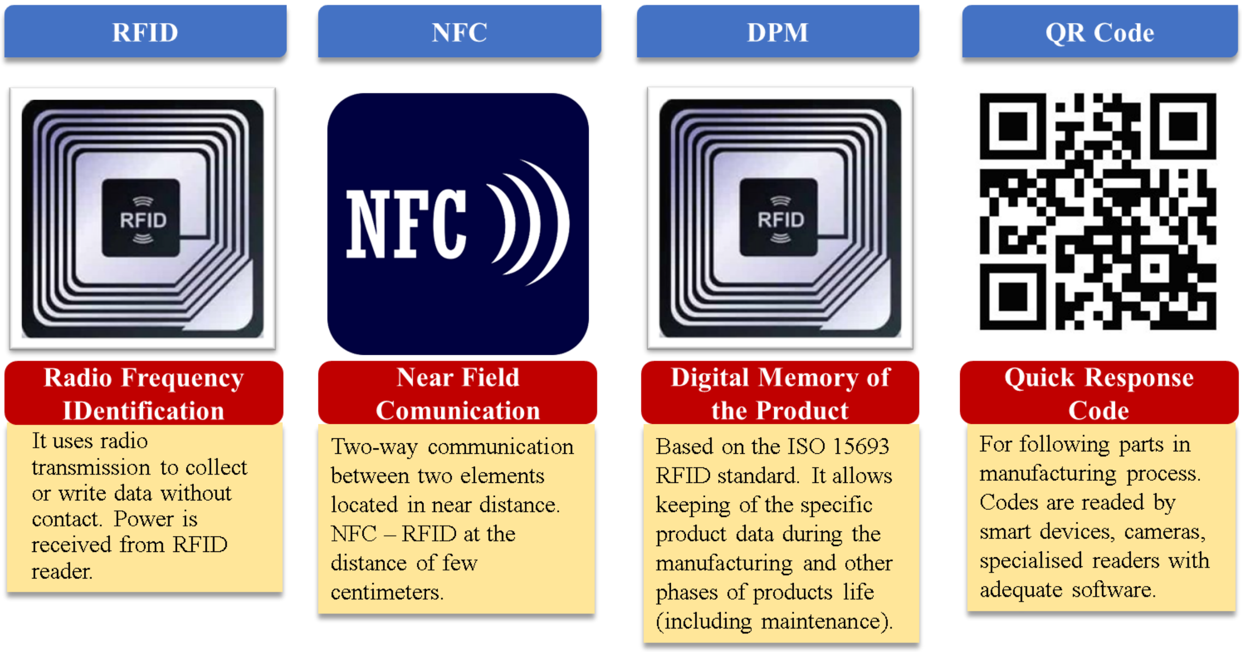

Fig. 1. Support for intelligent products in Industry 4.0

If part of recycling is taken into account, then reuse can be included in energy savings; but if it is considered a characteristic of a material that can change its configuration to be reused in the same or a different form, then it is a smart material. Resistance is the ability through which a product / part / material could retain its original shape.
Traceability is a technology that can be used to find the past and present location of unique objects as information-carrying entities [12]. However, the particular technology (sensing) which can be used to track entities is necessary. These sensors are called smart sensors. Advanced temperature sensors, as well as other smart sensors (pressure, force, speed, voltage etc.) are used today in the manufacturing of intelligent products. Other applications include the use of antimetal radio frequency identification (RFID) in production environments. When smart sensors have processors and software for efficient data exchange, they are called smart products / parts. Traceability is extremely important for providing location data; and if these data are used in the analysis, then they could be considered a part of the subsystem in Industry 4.0 for data analysis. Traceability can also be provided in real time, because then the monitoring of the object location is permanent and constant.
Smart materials can sense changes in the environment and sensor-assisted operations, take corrective action with actuators and provide data for analysis, which can further lead to improved part design (deformation and stress concentration simulation and calculation). Since smart materials require the use of sensors and actuators, they should be considered an element of Industry 4.0 [23]. Smart materials can also have the ability to change structure in response to external stimulation. Some of the most famous are piezoelectric materials and shape memory alloys. Therefore, a whole framework for Industry 4.0 can be defined, which includes smart products / parts / materials, Figure 2, which shows different characteristics and technologies that are part of smart products / parts / materials.

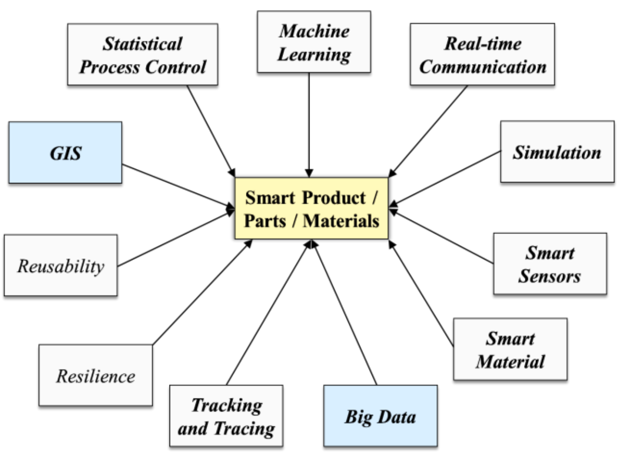

Fig. 2. Intelligent products and their characteristics for the Industry 4.0 concept

Industrial companies face major challenges: broken supply chains, shortened product life cycles, reduced time to market, increased product diversity, and increased scalability [23]. Introducing the concept of an intelligent product into the Industry 4.0 model implies improving production planning and management, greater production flexibility and changing of product variants. The presented analysis shows that intelligent products increasingly require the use of intelligent materials for their manufacturing, which gives a completely new research dimension.

4. STATE OF DEVELOPMENT OF INTELLIGENT PRODUCTS

Intelligent products are based on Artificial Intelligence (AI), which implies that Big Data Analysis techniques (BDA) and Machine Learning algorithms (ML) are used, with appropriate computer support.

At today's level of intelligent products development, their state can be shown by the scheme in Figure 3 [25], which includes four phases: monitoring (environment and use), management (connections with other devices and communication with the environment), optimization (BDA) and autonomy (ML and decision making).

The essence of intelligent products is their ability to manage knowledge about themselves, in the past, in the present, while predicting the future. For these reasons, big data is the key technology for them [26,27], with its following characteristics (5V): Value, Variability, Volume, Variety, Velocity. Another key technology is the Internet of Things (IoT) aimed at transferring, managing and using data. A key element of the intelligent product is the applied model of machine learning in the BDA. They are developed for different areas: natural language generation and speech recognition, text analysis, visual recognition, VR / AR, decision making, process planning, robotic process automation and deep learning, whereby most of them are also used for intelligent products.

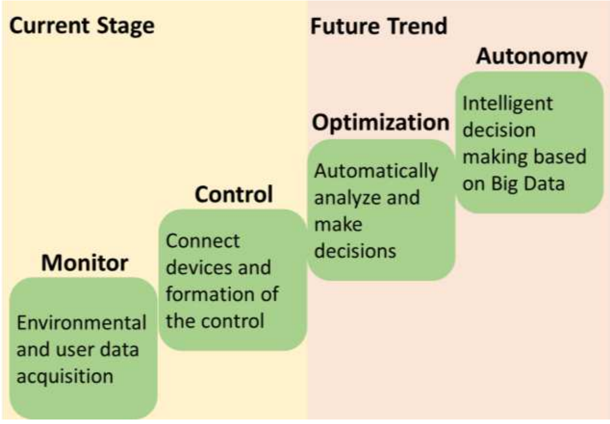

Fig. 3. Intelligent products in the context of Industry 4.0 [25]

An overview of machine learning algorithms that support these application areas is shown in Figure 4 [28]. For the field of intelligent products, the following algorithms are most often used: association rule learning, deep learning, decision tree, clustering and ANN.

The processing capacity of the hardware unit in intelligent products is very important, especially for data and algorithm-based AI. Graphics Processing Units (GPU), General Purpose Processors (GPP) and Field Programmable Gate arrays (FPGAs) are required to efficiently run AI-oriented computational tasks [29]. Hardware chips for intelligent products (CPU and GPU) should be energy efficient with very low latency (real-time operation), with quantum computing fully meeting these requirements.

System software should be organized into system clusters, with sets of instructions, libraries, and dedicated functions. It could be concluded that Artificial Intelligence (AI) and Machine Learning (ML) are the basic framework for the future development and application of intelligent products.

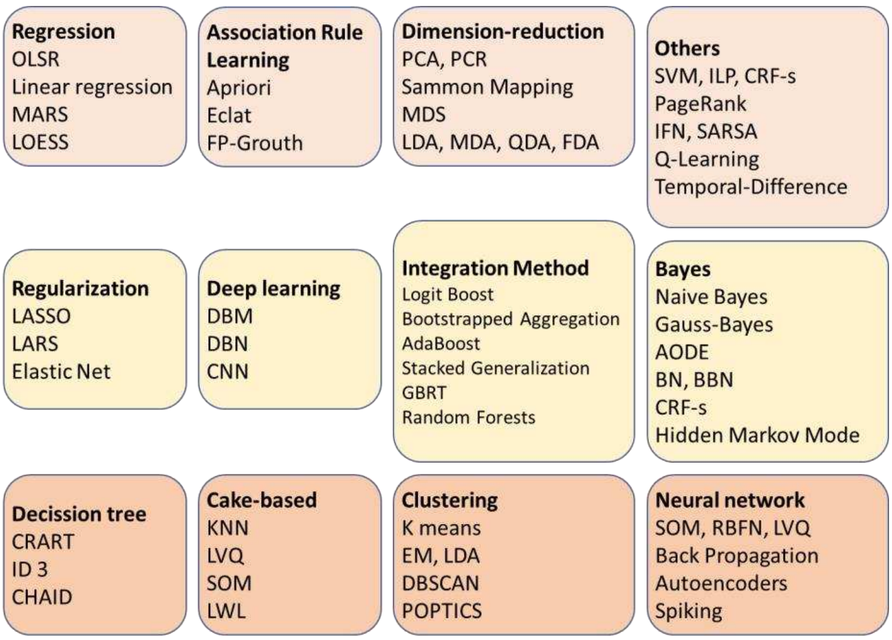

Fig. 4. Overview of machine learning algorithms [28]

5. DESIGN OF INTELLIGENT PRODUCTS

Today, intelligent products are researched, developed and manufactured based on market research and customer requirements, according to the AMC model [5]. Hence, these products have four phases of development: exploration period, market start-up period, high speed development period and market maturity period. At this time, the health care, consumer robots, domestic robots, smart cars, UAV (Unmanned Aerial Vehicle) and AR. The VR devices, industrial robots, wearable devices and smart home are grouped in the stage of market start-up [5]. This classification is market-based and shows the development of great potential for different products. As the chain of intelligent product industries expands to different areas, several possible profit models and markets will be explored in the future, Figure 5 [5].

The design of intelligent products differs significantly from the design of classic products due to: (a) their unique structure, Figure 6 [5], which represents the integration, most often, of MEMS components, microelectronics (hardware) and specialized software, (b) special user requirements, which are often not even defined, but the manufacturers are expected to define new needs and potentials [30], and (c) the necessary multidisciplinary knowledge, especially from AI and ML.

The main characteristic of an intelligent product should be its beauty (appearance) and practicality (ease) of use. However, the biggest difference compared to classic products are the technological factors that give them functional characteristics, which make up the intelligent transformation of products.

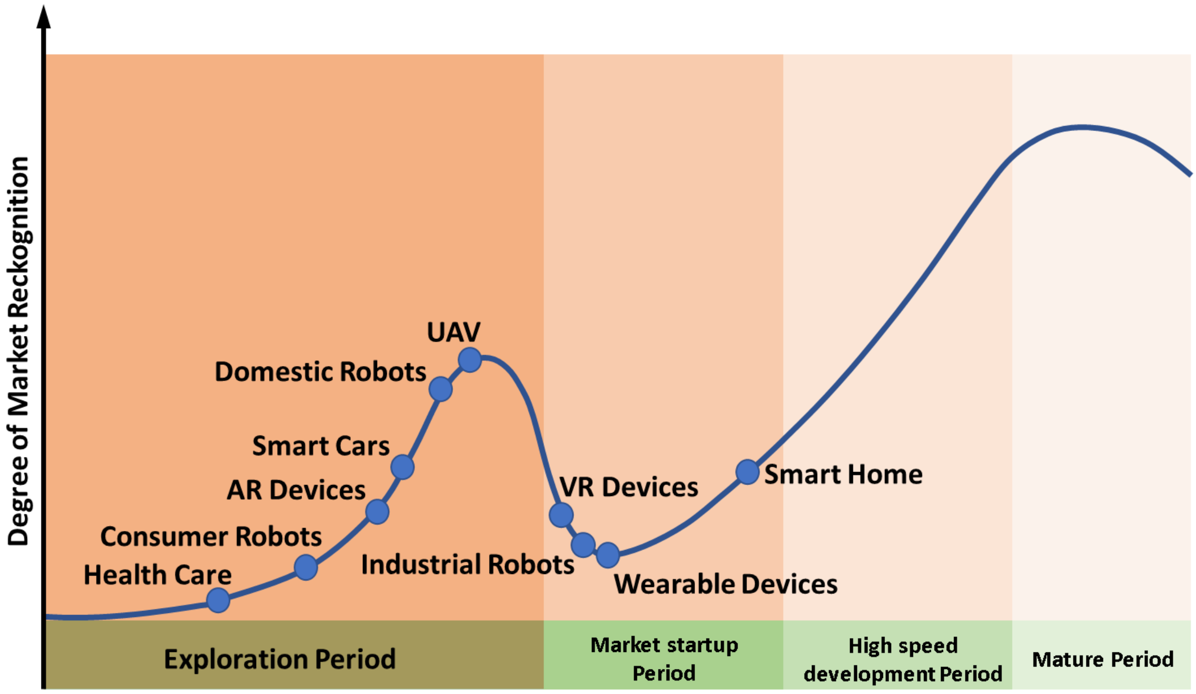

Fig. 5. The AMC curve of intelligent products (example for China - 2017) [5]

Sensor module		Communication module
Operating system module		
Power module	Structural component module	Extended function module

Fig. 6. Basic structure (modules) of intelligent products [5]

The main characteristic of an intelligent product should be its beauty (appearance) and practicality (ease) of use. However, the biggest difference compared to classic products are the technological factors that give them functional characteristics, which make up the intelligent transformation of products.

The most important feature of intelligent products in the design phase should be focus on the customer (user). This means that methods of researching the user needs should be used first, in order to define their basic requirements, and then supplemented with the expected benefits, Figure 7 [31]. Therefore, designers should be constantly informed about the feedback on new customer requirements, as well as their opinions on the newly launched products.

In the future, the user-centred design will focus on developing models for interpreting cognitive processes, which are created by users' thinking about an intelligent product (when s/he already uses the product or thinks about what the product should be like), which produces psychological associations and creates neural mechanisms. They should compensate for the weaknesses of explicit research on user requirements and improve the reliability of these methods. Today, the following methods of implicit measurement of user requirements are used: Implicit Association Test (IAT), Electroencephalograph (EEG) and Functional Magnetic Resonance Imaging (FMRI) [32].

A new method that is being increasingly used in the context of Industry 4.0 is data mining, as well as direct user participation.

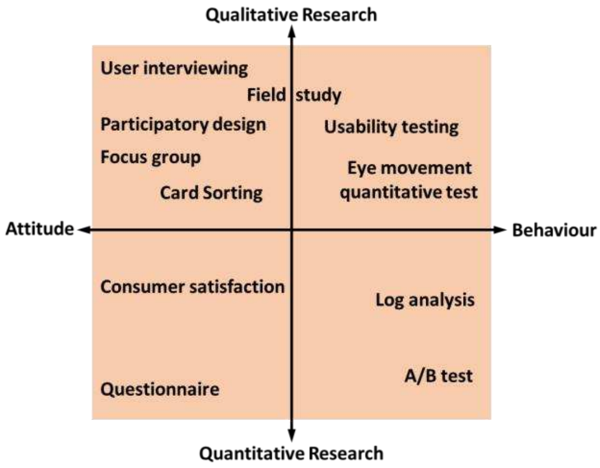

Fig. 7. Classification of user requirements research methods [31]

Engineering design using CAD systems in this area should be used to help the designer to enhance the aesthetic dimensions of products and their creative possibilities, which means that they should have the best visualization functions. These functions are especially important in the application of rapid prototyping technologies, as well as in the application of virtual approaches in the Industry 4.0 model, such as digital twins. Another dimension of this area is the cognitive complexity of these products, which requires additional collaborative work with more specialties, with consideration of: product complexity, their multidisciplinarity (primarily in structure), domain integration and market globalization trends [33].
Starting from the previous analyses, it is possible to define the basic principles of intelligent product design: technical support (a smart product that can communicate naturally), interconnection (intelligent products form a network) and service content, Figure 8 [5].

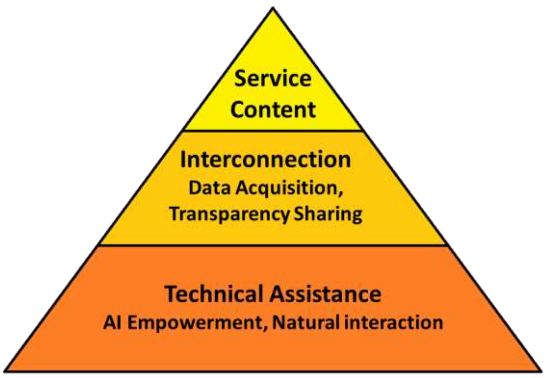

Fig. 8. Basic principles of intelligent product design [5]

Technical support is related to AI technology, because sensors with this technology and deep learning ability (speech and image recognition, video analysis and semantic understanding) are used in intelligent products. This allows intelligent products to possess visual, tactile, auditory and other active abilities. Natural interaction means that these products are beginning to use natural forms of interaction, not just mouse and keyboard, but also: touch, speech, gestures, handwriting and vision. Image interaction is based on the application of machine vision, through the perception and recognition of image content. The most natural interaction is via voice, because 80% of human communication is performed in this way, which means that intelligent products also have the function of recognizing natural language. Behavioural interaction is based on tracking natural movements and physical location in order to predict the intention of the user.
The interconnection of different intelligent products creates a multidimensional network of intelligent perception, whose big data are transparently collected and stored in the cloud. Their BDA is performed on that platform, through distributed planning and management of interaction with network entities. Only interconnected and interoperable data, i.e. knowledge, form a functional system. It is a fusion of the physical and virtual world, with the connection of sensory data with digitized models of intelligent products, a virtual copy of the physical world, i.e. a digital twin [6]. The communication module is one of the most important parts of an intelligent product, which enables the connection of objects and the exchange of information. With the help of IoT, intelligent products communicate with each other, cooperate with their neighbouring "smart" components and achieve common goals, applying unique addressing schemes. The communication technologies used here are: RIFID, Wi-Fi, Bluetooth, ZigBee, ultra-wideband (UWB) radio technology and mobile communications GPRS, 3G, 4G, and 5G technologies. In this way, intelligent products (machines and devices), sensors and people are connected via the IoT, IoP (Internet of People), or IoE (Internet of Everything).
An example is the Xiaomi smartwatch, which has a built-in three-dimensional rhythm motion sensor to collect information on user movement, exercise data, number of steps, sleep quality and calorie consumption. When all these data are passed to the cloud, using the BDA and ML model, the user receives feedback and recommendations to improve their health. Even today, there are intelligent products that cover various aspects of life (health care, physical appearance and sports), traffic, housing, manufacturing, etc.

6. LEVELS OF INTELLIGENT PRODUCTS – A CASE STUDY

Research, development and application of intelligent products has been going on for over two decades. This allows the definition of the four achieved levels of development of intelligent products (the digital, connected, responsive and intelligent level). An important feature is that each subsequent level contains and encompasses all the characteristics of the previous level. An overview of these levels is given in Table 2 [4].
This categorization of intelligent products was performed according to 17 criteria [4], whose basic features are included in Table 2.

Table 2. Levels of development of intelligent products (supplemented according to [4])

	Level 1- Digital (to the 2000)	**Level 2 – Connected** (2000-2010)	**Level 3 - Responsive** (2010-2020)	**Level 4 – Intelligent / Industry 4.0** (after 2020)
Hardware & Software support	Basic hardware Software for basic operating	Basic hardware Connectors Sotware for communication	Basic hardware Connectors Sensors & Actuators Sotware for define pre-sensing and responding logic (SRL) and programmable SRL	Basic hardware Connectors Sensors & Actuators Sotware for define pre-sensing and responding logic (SRL) and programmable SRL AI software for learning, improving and anticipating
Capability	ITT Equipped Data storage Data processing &analysis Data provision & transmission	+ Unique identification Networking & Connectivity Communication & Information Exchange Interaction & Cooperation	+ Sensing Real time context – awarness Reactivity & Adaptability Automated Actuation Functionality & Customization	+ Reasoning & Decision making Autonomy & Self- management Proactivity
Application (functions & services)	Predefined input and output operations (digital camera) Basic settings (radio station or alarm setting, hi-fi system) Entering, storing and displaying of information (Apply iPod) Car digital panel	Tracking services (Smart meter) Dispersed funcionality (Samsung (Philips) Hue Lighting System) Remote control and monitoring (wirelees printer) Infotainment (Audi connect)	IFTTT routines (Amazon Echo) Rule-based skill and actions (Gougle Home actions) Reactive actions (car lane assist) Deterministic automated action (Amazon Dash Shelf) Location & data-based services or navigation tasks (route optimization) Performance tracking (Apple Watch)	Complex context-based services (NEST Learning Thermostat) Procative services (anticipatory services in the AI CON car) Complex learning-based and self-organizing autonomus actions (driverless vehicles)

This categorization of intelligent products was performed according to 17 criteria [4], whose basic features are included in Table 2. This classification is supplemented in Table 2 by the time dimension, which should be understood conditionally, but in the context of development and application of Industry 4.0. Another important feature of these levels is that these products also include service as an integral part of the product, which represents a new direction of research and development of intelligent products.

Starting from the definition of CPS in Industry 4.0, it could be concluded that the difference between the essential definition of CPS and intelligent product is slowly but surely being erased, so it could be expected that they will become the same thing in the next (fifth) level of intelligent products.

It should also be noted that the given examples of the levels of intelligent products from Table 2 refer, in most cases, to the automotive industry. It should be said that other examples can be found in the medical-pharmaceutical field, production of computers, personal medical-entertainment devices for everyday use, mobile phones, home appliances and devices and public services. For other industries, the concept of intelligent products is at the beginning of development and application.

The digital product is supported by hardware and IT elements (storage, processing, display and data transfer). These elements improve the characteristics of the product through its additional features (digital cameras, MP3 players, hi-fi systems, digital panels in cars) [4].

A connected product has the following features: original identification, networking and connectivity, communication and exchange of information, interaction with the user and other entities and cooperation with them [4]. In order to realize these functions, it must have basic computer support and connectors, as well as communication software for connection to the entity network using IoT. Entities receive and send data, and hence, by interacting with other products, they create added value, increasing their functional characteristics. The original digital entity identification enables automatic detection, location and tracking of entities during their lifetime, as well as their activities. Technically, communication is achieved through a range of available network technologies: wireless internet technologies, Bluetooth or high-frequency RFID tags. By exchanging information with each other and working together, this level of products creates sets of IoEs (Internet of Everything). The examples of this level of products include [4]: automatic ordering (Amazon Dash), the smart lighting system (Philips Hue), smartphone, the music system or the smart home assistant, via voice-control. In this way, different interconnected products and agents jointly create value.

A responsive product has the following features: sensing, working in real-time, reactivity and adaptability, automated actuation, functionality and customization [4]. This level of intelligent products has basic hardware support, connectors, sensors and actuators. As far as software is concerned, it supports software for defined pre-sensing and responding logic (SRL) and programmable SRL, which allows it to work in feedback logic. This means that sensors are the key technology that characterizes these products, such as: the Audi A8 with central driver assistance control (zFAS), or the Audi "active lane assist" or the brake assistant "pre sense 360" [4]. These features allow these products to gain real-time environmental awareness (location, humidity, sound, temperature or weight), which means they are subject to the BDA analysis to maintain and monitor performance, as well as generate new reactivity and adaptability actions (safe braking distance for different conditions, etc.). All this implies that this level of products not only feels and observes, but also follows (re)actions based on observations, through actuators. Actuator actions can be physical (robot vacuum cleaner) or virtual (Amazon Dash Shelf), where the process of informing the customer is virtually started and the order proposal is activated. These automated actions use IF-This-Then-That-Type (IFTTT) operations, which give the product autonomy from the user's point of view. Thus, this type of product works within the defined sets of operational parameters, where two types of functional products could be distinguished: (a) those that follow a predefined detection and response logic (SRL), and (b) programmable SRL. The product that follows the predefined SRL works on the basis of one-dimensional operating parameters (Amazon Dash Shelf). In contrast, products that follow programmable SRLs are based on more versatile functionality and can be programmed using ideas and skills (Google and Amazon allow their users to customize their Google Home or Amazon Echo) or also provide platforms for developers, allowing users to program the IFTTT routines. Hence, we get the "tailoring of products according to buyers' and consumers' needs and affects", creating a highly personalized product through the provision of customized functions and services [4]. A real example are ski boots Atomic Connected [4], which have motion and acceleration sensors, where the system monitors ski performance: slope and speed, path length, turns, distances and altitude, and also registers how well someone stands on the skis. The device in the shoe generates feedback and informs the user via mobile phone how to improve skiing in terms of smarter, safer and better skiing. Another example [4] is Amazon Dash Shelf, which uses virtual actuators to initiate orders, with demand forecasting, and BDA-based delivery analysis.

Finally, the last level refers to intelligent products in the context of Industry 4.0, which means that they have the following characteristics: reasoning and decision making, autonomy and self-management and proactivity [4]. These features allow products to be able to learn, anticipate and act independently, while the products are supported by appropriate hardware and complex AI software (networking, responding to changes in the environment, reasoning and learning). The ability to reason and make decisions, about itself and in interaction with external entities, makes these products intelligent. They are supported by tools and techniques of AI for deep machine learning (for example ANN), which allows products to think reactively and make conclusions while learning from new situations, which leads to new adaptation and increased autonomy. BDA analyses are used for all this, which adds a dimension of predictive analytics (early warning system or failure detection) to these products. The best examples of this product level are: AlphaGo Zero - AI DeepMind (AI integration and decision making), autonomous vehicles (Audi, Mercedes), or NEST Learning Thermostat, which develops intuition about its users and predicts habits through predictive BDA, managing climate parameters at home according to the habits of the tenants (for example when no one is at home, some devices are turned off and the temperature is reduced) [4]. The latest example, which comes from the company ZF (Germany), is the minibus e.Go Mover. This intelligent product uses sensors and software support based on AI and ML, which monitor the vehicle, driving and infrastructure, generate responses from the environment and develop its cognition and adaptation, in order to achieve independent driving [4].

7. CONCLUSION

Smart product is a concept that is developing rapidly, primarily due to the rapid development of the IT industry. As the analysis shows, smart products require knowledge from various fields of engineering and informatics. Levels of intelligent products provide an overview of their development and directions for future research in this area. In this context, it is important to emphasize that Industry 4.0 is the best framework for research and development of intelligent products nowadays. As far as Serbia is concerned, research in this area is still at the development stage, and it has two directions: (a) industrial applications and development that is parallel to the application of this concept in the organizations (such as Servotech, Inmold), and (b) scientific research at faculties and institutes. So far, Faculty of Mechanical Engineering at the University of Belgrade has significantly contributed to the development and implementation of the national program for Industry 4.0 in Serbia. This work should also be understood as a new effort towards spreading the scientific-research culture of smart products in the Republic of Serbia.

REFERENCES

[1] Holler, M., et al., Understanding the Business Value of Intelligent Products for Product Development in Manufacturing Industries, ICIME 2016: Proceedings of the 2016, 8th International Conference on Information Management and Engineering, November 2016, Pages 18–24. https://doi.org/10.1145/3012258.3012266.

[2] Dimitris Kiritsis, Closed-loop PLM for intelligent products in the era of the Internet of things, Computer-Aided Design 43 (2011) 479–501, www.doi:10.1016/j.cad.2010.03.002.

[3] Tomás Sánchez López, et al., Taxonomy, technology and applications of smart objects, Inf Syst Front (2011) 13:281–300, www.doi:10.1007/s10796-009-9218-4.

[4] Stefan Raff, et al, Smart Products: Conceptual Review, Synthesis, and Research Directions, J Prod Innov Manag 2020; 37(5):379–404, www.doi:10.1111/jpim.12544.

[5] Jiarui Wang, et al., Research on the Design Principles for Intelligent Products, Springer Nature Switzerland AG 2019, A. Marcus and W. Wang (Eds.): HCII 2019, LNCS 11583, pp. 351–367, 2019. https://doi.org/10.1007/978-3-030-23570-3_26.

[6] Ilya Kovalenko, et al., The model-based product agent: A control oriented architecture for intelligent products in multi-agent manufacturing systems, Control Engineering Practice 86 (2019) 105–117, https://doi.org/10.1016/j.conengprac.2019.03.009.

[7] Julia Hofmeister Kahle, et al., Smart Products value creation in SMEs innovation ecosystems, Technological Forecasting & Social Change 156 (2020) 120024, https://doi.org/10.1016/j.techfore. 2020. 120024.

[8] Dharmendra Kumar Mishra, et al.. Towards Realizing the Smart Product Traceability System. 9th IEEE International Conference on Software, Knowledge, Information Management & Applications (SKIMA 2015), Dec 2015, Kathmandu, Nepal. https://doi.org/10.48550/arXiv.1811.09693.

[9] Andreas Riel, et al., An architectural approach to the integration of safety and security requirements in smart products and systems design. CIRP Annals - Manufacturing Technology, Elsevier, 2018, 67 (1), pp.173-176. www.doi:10.1016/j.cirp.2018.04.022.

[10] Dawid, H., et al. Management science in the era of smart consumer products: challenges and research perspectives. Cent Eur J Oper Res 25, 203–230 (2017). https://doi.org/10.1007/s10100-016-0436-9.

[11] Gerben G.Meyer, et al., Intelligent Products: A survey, Computers in Industry, Volume 60, Issue 3, April 2009, Pages 137-148, https://doi.org/10.1016/ j.compind.2008.12.005.

[12] Paul Valckenaers, Hendrik Van Brusse, Intelligent products: Intelligent beings or agents?, IFIP International Federation for Information Processing, Volume 266, Innovation in Manufacturing Networks; ed. A. Azevedo; (Boston: Springer), pp. 295–302, 201.

[13] Thorsten Wuest, et al., Digital Representations of Intelligent Products: Product Avatar 2.0, Proceedings Abramovici, M., & Stark, R. (Eds.). (2013). Smart Product Engineering. Lecture Notes in Production Engineering. www.doi:10.1007/978-3-642-30817-8.

[14] Reiner Anderl, et al., Smart Engineering for Smart Products, Proceedings Abramovici, M., & Stark, R. (Eds.). (2013). Smart Product Engineering. Lecture Notes in Production Engineering. www.doi:10. 1007/978-3-642-30817-8.

[15] Chien Yaw Wong, et al., The intelligent product driven supply chain, IEEE International Conference on Systems, Man and Cybernetics, 2002, volume 4, pages 6 pp. www.doi:10.1109/ICSMC.2002. 1173319.

[16] McFarlane, Duncan, et al., (2002), The Intelligent Product in Manufacturing Control and Management. IFAC Proceedings Volumes, 35(1), 49–54. www.doi:10.3182/20020721-6-es-1901.00011.

[17] Blake Ives, Michael R. Vitale, After the Sale: Leveraging Maintenance with Information Technology, MIS Quarterly, Vol. 12, No. 1 (Mar., 1988), pp. 7-21, http://www.jstor.org/stable/248797. Accessed March 2022.

[18] Duncan McFarlane, Auto ID systems and intelligent manufacturing control, Engineering Applications of Artificial Intelligence, 16(4):365 - 376, 2003. www.doi:10.1016/S0952-976(03)00077-0.

[19] M. Kärkkäinen, et al., Intelligent products - a step towards a more effective project delivery chain. Computers in Industry, Vol. 50:141-151, 2003. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.64.4722&rep=rep1&type=pdf. Accessed March 2022.

[20] Olli Ventä, Intelligent products and systems, Technical report, VTT, 2007. https://cris.vtt.fi/en/publications/intelligent-products-and-systems-technology-theme-final-report. Accessed March 2022.
[21] Carabelea, C., et al., (2003), Benefits and Requirements of Using Multi-agent Systems on Smart Devices, Lecture Notes in Computer Science, 1091–1098. www.doi:10.1007/978-3-540-45209-6.
[22] Kary Främling and Jan Holmström. Design patterns for managing product life cycle information. In Proceedings of 18th International Conference on Production Research (ICPR), 31 July to 4 August 2005, Salerno, Italy, 2005. http://www.cs.hut.fi/~framling/Publications/ICPR2005articleKF.pdf. Accessed March 2022.
[23] Sameer Mittal, et al., Smart manufacturing: Characteristics, technologies and enabling factors, Proc IMechE Part B: J Engineering Manufacture, 2019, Vol. 233(5) 1342–1361, www.doi:10.1177/0954405417736547.
[24] Rijsdijk, S.A., et al., Product intelligence: its conceptualization, measurement and impact on consumer satisfaction. J. of the Acad. Mark. Sci. 35, 340–356 (2007). https://doi.org/10.1007.
[25] IResearch, China Business Intelligence Industry Research Report (2021). http://report.iresearch.cn/report/202106/3010.shtml. Accessed March 2022.
[26] Amir Gandomi, Murtaza Haider, Beyond the hype: Big data concepts, methods, and analytics, International Journal of Information Management, Volume 35, Issue 2, 2015, Pages 137-144, https://doi.org/10.1016/j.ijinfomgt.2014.10.007.
[27] Fan, Wei, and Albert Bifet. "Mining big data: current status, and forecast to the future." ACM sigkdd explorations newsletter 14.2 (2013): 1-5. https://doi.org/10.1145/2481244.2481246.
[28] Sarker, I. H. (2021). Machine Learning: Algorithms, Real-World Applications and Research Directions. SN Computer Science, 2(3). www.doi:10.1007/s42979-021-00592-x.
[29] Lu, H., et al. Brain Intelligence: Go beyond Artificial Intelligence. Mobile Netw Appl 23, 368–375 (2018). https://doi.org/10.1007/s11036-017-0932-8.
[30] Wenjin Yang, et al., Intelligent Design of Product Forms Based on Design Cognitive Dynamics and a Cobweb Structure, Computational Intelligence and Neuroscience, Volume 2021, 17 pages, https://doi.org/10.1155/2021/6654717.
[31] Zawadzki, P., Żywicki, K. (2016), Smart Product Design and Production Control for Effective Mass Customization in the Industry 4.0 Concept, Management and Production Engineering Review, 7 (3). www.doi:10.1515/mper-2016-0030.
[32] Bin Zhou, Li Lin, Research on Cognitive Matching of Biological Morphological Features and Images for Profiling, Design, E3S Web of Conferences 179, 01015 (2020), EWRE 2020, https://doi.org/10.1051/e3sconf/202017901015.
[33] Senthil K. Chandrasegaran, et al., The evolution, challenges, and future of knowledge representation in product design systems, Computer-Aided Design, Volume 45, Issue 2, 2013, Pages 204-228, https://doi.org/10.1016/j.cad.2012.08.006.

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SENSORY TECHNOLOGY IS ONE OF THE BASIC TECHNOLOGIES OF INDUSTRY 4.0 AND THE FOURTH INDUSTRIAL REVOLUTION

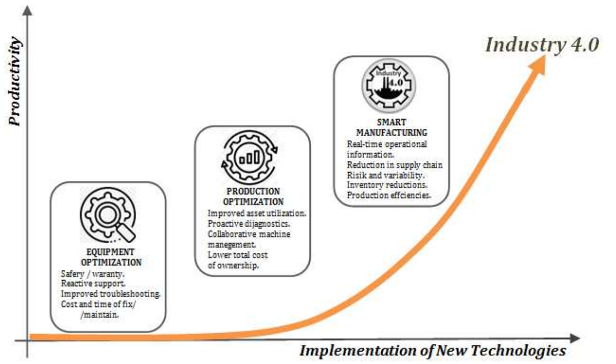
Isak KARABEGOVIĆ

Abstract: *Digital transformation of the production process or the entire value chain, from component to system and from supplier to customer, is the key to hidden value that can contribute to the company's productivity, compliance, profitability, and quality of the finished product. Connected production processes in the company are realized by converging information technology (IT) and operational technology into a single one, which results in the introduction of flexible industrial automation of production processes. These technologies connect the physical and virtual worlds with the Internet of Things (IoT) in order to better collect and analyze data, turning it into information that reach the decision-makers. All of the above cannot be achieved without the implementation of smart sensors that provide information at all times. Industry 4.0 can be implemented in production processes only by using smart sensors, and they, along with other technologies, are responsible for fully flexible automation of production processes, which brings a number of advantages such as shortening product development time and reducing manufacturing costs. The application of smart sensors makes production processes more efficient, and we have the ability to optimize them. The paper presents the basics of smart sensors, their role in Industry 4.0 as well as examples of their implementation in production processes.*

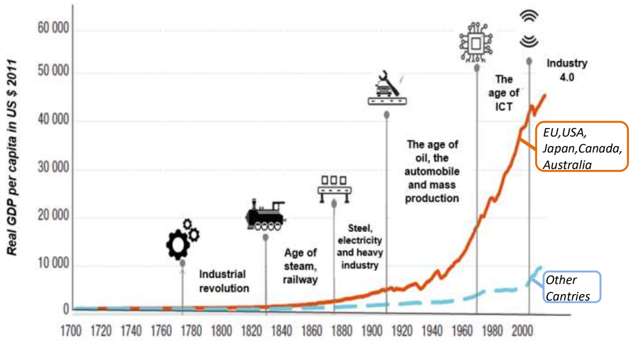
Keywords: *smart sensors, Industry 4.0, implementation, production system*

1. INTRODUCTION

All companies in the world as facing global competition, and in order to keep up with the competition and meet the growing demands of the market, it is necessary to use new technologies in production processes, i.e. implement Industry 4.0. In other words, digital transformation is needed to make a connected company that enables production processes to discover new ways to increase productivity and improve overall business performance. Industry 4.0 helps to increase productivity as well as improve the company's overall business performance [1,2,3]. To ensure this, it is necessary to have a secure connection between the various production systems and processes throughout the company. The new way of managing production processes aims to improve performance, make better use of data that already exist, and use a combination of tools that can improve the system or production process. The digitalization performed throughout the company, integration of processes, serial and discrete, drives, and movement into one connected infrastructure increases efficiency and productivity in all segments of companies. The access to production data in the production process at any time in real time allows us to monitor and improve the performance of the production process itself. Many companies around the world have developed different sensor designs to measure different physical sizes [1,7,8,9]. Currently, great changes are happening every day in all industries, including the transformation of production processes, increasing flexible automation of production processes, new form of delivery of finished products, and a new way of consumption, all thanks to the implementation of Industry 4.0. The basic technologies on which Industry 4.0 is based are: robotics and automation, smart sensors, Big Data, Internet of Things (IoT), 3D printing, radio frequency identification (RFID), virtual and augmented reality (AR), artificial intelligence (AI), advanced security systems, etc. [10-13]. The application of Industry 4.0 brings a number of advantages such as flexible automation, and bridging the physical and digital world through cyber physical systems (CPS). Greater and more open integration in manufacturing companies is enabled by cyber physical system (CPS) and Internet of Things (IoT) through horizontal integration (reflected in the exchange of information and data, networking of production processes, communication integration: procurement-production-logistics, and inclusion of customers in the production process), and vertical integration (connectivity in the company from the operational level to the production itself). The implementation of base technologies can optimize the following: equipment in the production process so that we have greater safety, improved problem-solving, equipment safety, improved maintenance, self-production so that we improve the use of tools, proactive diagnostics, collaboration and management machines, and lower total costs [14-19]. The goal of implementation of Industry 4.0 core technologies is smart manufacturing where we have real-time operational information, reduce supply chain risk, reduce inventory, achieve the efficient production (Figure 1.a), as well as growth of GDP (Figure 1.b). It is necessary to build a set of skills both inside and out. An illustration of how to achieve smart manufacturing using Industry 4.0 implementation in companies is shown in Figure 1.



a – application of base technologies of Industry 4.0 increases productivity



b – the impact of technological change on GDP growth

Fig. 1. Implementation of base technologies of Industry 4.0 -a, and their impact on GDP growth – b [6]

A graphical representation of the implementation of base technologies in Industry 4.0, their impact on technological change and inequality over the centuries, and GDP growth are shown in Figure 1. The analysis of Figure 1.b) has shown that the biggest jump in living standards due to investment in research, development and the implementation of advanced technologies happened in the last fifty years. Worldwide, many leading companies are investing and implementing advanced technologies that are key Industry 4.0 technologies. These companies have made significant progress thanks to artificial intelligence, machine learning, and an increase in available data growing exponentially, as well as the improvement of statistical methods and advanced data analysis in digitization and automation in production processes. All this has been happening in the last ten years.The accelerated implementation of advanced technologies in Industry 4.0 has been significant since 2016, when the Fourth industrial revolution was announced at the World Economic Forum. In order to survive and be present in the global market, it is necessary for companies to optimize equipment, which must be reliable and safe, minimize equipment downtime, and improve problem solving. It is necessary to optimize the production processes (as shown in Figure 1-a) that are active in companies through improving the use of devices and machines, collaborative management of machines, proactive diagnostics, and reduction of overall costs. By introducing the technologies that form the foundation of Industry 4.0, we have real-time operational information and can act instantly which makes production efficient, reduces risk and supply chain variability, thus reducing inventory. The implementation of advanced Industry 4.0 technologies would not be possible without the use of smart sensors, defined by the IEEE 1451 Standard. The enhanced development of robotic and sensor technology, supported by information and communication technologies, is moving in the direction of communication between robots and humans, and the machines themselves.

2. SMART SENSORS AND THEIR CAPABILITIES IN PRODUCTION PROCESSES

Companies in the world engaged in the research, development and production of sensors for measuring different physical quantities have developed different sensor designs. Today, companies are in the phase of transformation of production processes, because they want to achieve greater automation of production processes with greater flexibility due to the higher customer requirements and survival in the global market. The implementation of advanced Industry 4.0 technologies such as: Internet of Things (IoT), Big Data, 3D printing, robotics, smart sensors, artificial intelligence (AI), virtual and augmented reality (AR), etc., provided a new way of consumption and a new form of delivery to the customer, since the customer wants to be involved in the production process. The implementation of Industry 4.0 cannot be achieved without the implementation of all the above mentioned advanced technologies. However, we must single out the basic sensor technology, because without the implementation of various smart sensors we could not monitored parameters in real time [1,3,17,18,20,21,22].Since there has been a development in all segments of society in all technologies, there has also been a historical development of sensors. The schematic representation of the development of sensor technology over time is given in Figure 2. Based on Figure 2, we can conclude that sensor technology has had continuous development from the first mechanical sensors, electrical sensors, and electronic sensors. Today smart sensors are being researched, developed and implemented to support the implementation of Industry 4.0 in production processes. By implementing smart sensors in all processes, as well as in production processes, we can monitor and obtain a large amount of data on the basis of which we make decisions.

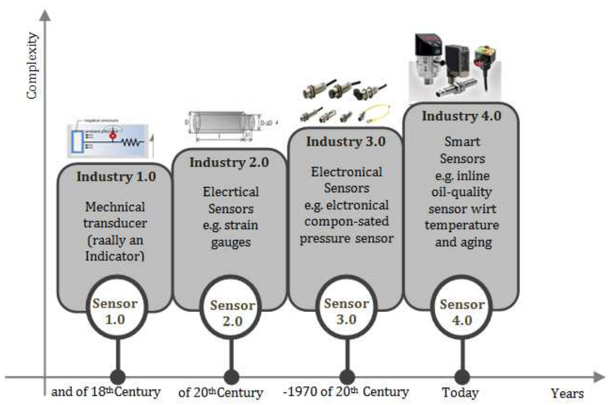


Fig.2. Schematic representation of the development of sensor technology over time

Given that the world's leading companies are in the process of implementing Industry 4.0, and they are trying to follow other companies in the world to remain in the global market, the possibility of increasing the use of sensors, and thus improving the manufacture of products is reflected in the following [1,3]:

- Sensors help to detect defects, allowing quick adjustment of settings and change of parameters to prevent downtime in future production processes.
- Based on data provided by smart sensors and insights gained from production to the delivery process, the entire supply chain is managed much more efficiently.
- Scheduled machine maintenance allows companies to more effectively plan downtime and prevent downtime or breakdowns during the manufacturing process.
- Increases efficiency and productivity by integrating smart sensors.
- We are able to quickly change the production process of one product to the production of another product.
- Adaptation of the production process for another product is simulated practically before it is physically implemented in order to adequately assess the impact and reduce the chances of errors.
- Implementation of smart sensors leads to smart machines and devices.
- Analysis of data obtained through smart sensors helps to identify and prevent dangerous situations, and thus improves the health and safety of workers.
- Their implementation ensures planned maintenance and quality control.
- Energy consumption can be optimized by using advanced analytics, because we can monitor energy consumption and make decisions by using smart sensors.

We can maintain optimal productivity and efficiency at all times if we have information about what is happening on machines that are installed in production processes minute by minute. We are also able to avoid unplanned downtime and losses that occur in the production process. The integration of smart sensors provides us with all the necessary data to create a comprehensive image of the production processat every moment. The implementation of smart sensors enables the introduction and operation of smart machines that increase the productivity and efficiency of the production process. Their installation in the production process enables all possible parameter: temperature, pressure, flow level, movement to distance, control of the accuracy of the performed operation, monitoring of the production process, and many other parameters that we have not listed. We are able to have a comprehensive overview of the production process. By knowing the current situation in the production system and the state of the sensor, we can ensure and timely identify any type of potential malfunction in the production process, as well as the sensor itself. The installation of smart sensors in the production process with other necessary equipment is shown in Figure 3 [3]

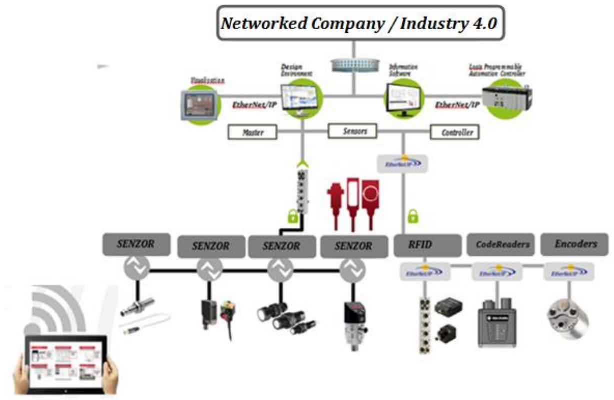


Fig.3. Scheme of installation of smart sensors in the production process with accompanying equipment

The continuous flow of valuable process and diagnostic data, and the visualization system are enabled by smart sensors with informative software and programmable controllers, as shown in the configuration diagram in Figure 1. In this way, the company is connected, which provides efficiency and other advantages. Creating a connected company using smart sensors and smart machines reduces the complexity of production processes and errors [23,24,25].

They simplify access to available data that can help achieve overall equipment efficiency and average time between failures. Real-time diagnostics optimizes preventive maintenance and problem-solving that arises in the production process, which enables us to reduce the solution time by about 90 % [28]. The change time for each sensor is reduced, and there is the possibility of automatic device configuration to reduce the error when replacing the sensor. Within each production process there are many operations such as: material handling, material transport, execution of certain operations, assembly, packaging, varnishing, sorting, etc., which require smart sensor so that we can have data on the smooth performance of the operation.

When implementing sensors, we must identify key operations within the production system and define the area of focus in which we need to verify the conditions.

We need to know what the system is doing or what we want it to do, such as counting products, performing quality checks, orienting parts, etc.[28,29,30]. We need to know what the feedback is for each function, as well as what conditions must be met after each function to confirm that the function was performed correctly. When we have identified the areas in which the action takes place in the production process, it is necessary to make an analysis of whether each area is so important from the point of view of automation of the production process and monitoring data important in the production process.
As we have seen, the application of smart sensors can occur in any production process. We need to choose the parameters to be monitored, make the right decision to install the appropriate smart sensor with other selected technology and continue to monitor the performance of appropriate tasks in the production process on mobile devices, as shown in the example in Figure 4.

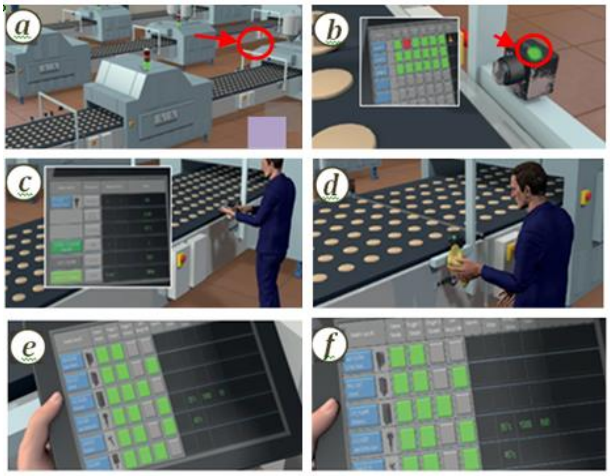


Fig.4. Implementation of smart sensors for collecting information in the production process

As Figure 4 shows, we are able to obtain information about performing operations on a mobile device. For the sake of illustration, Figure 4 shows the production process in which real-time data is monitored. The machine works normally (Figure 4.a)) and is monitored by mobile devices using smart sensors. Data is processed and monitored including activated output and measured data, the accuracy of the sensor, the state of communications, as well as data flow. It is observed that the sensor detects dust accumulation (Figure 4.b)). The operator has information about the type of sensor and where it is placed in the production process (Figure 4.c)). He provides information for maintenance, which act in a timely manner and eliminate the malfunction (Figure 4.d)), thus returning safe operating parameters (Figure 4.e)). Therefore, the monitoring of the production process can continue (Figure 4.f)). In this way, we can monitor the operation of all parameters of the production process that are important for that process at any time, so that we can take necessary measures and eliminate the shortcomings and allow the production process to work without errors. By implementing smart sensors in the production process, we are able to quickly adjust the production process for the production of another product, i.e., the transition from the production of one product to the production of another is very simple, as shown in Figure 5.
If the production process is set to manufacture one product, e.g., product (A) which we monitor using smart sensors, the setting of all parametersis defined for product (A), as shown in Figures 5.a and b). If we want to stop the product (A) and switch to the production of the product (B), we must give the command for that product on the mobile device, as shown in Figure 5.c).

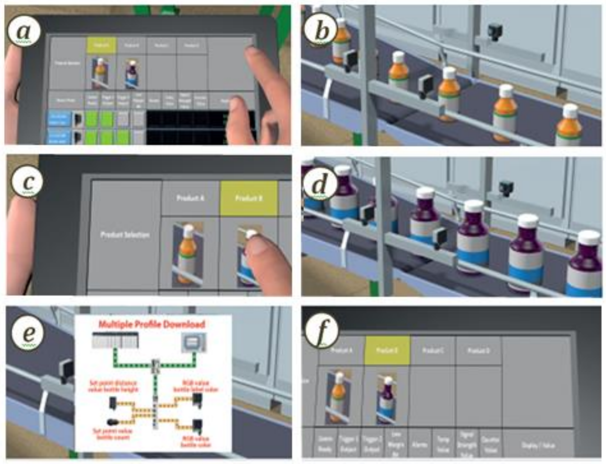


Fig.5. Adjusting the production process to manufacture another product using smart sensors

The production of product (B) is initiated (Figure 5.d)) and profiles for four sensors that monitor the parameters in the production process (Figure 5.e) are downloaded. Smart sensors set new parameters for product (B) so that the machine is ready to manufacture another product. By implementing smart sensors in the production process, we can supervise, monitor, and control certain parameters when performing tasksat any time, all depending on which parameters are necessary for the production of the finished product to run smoothly. For the sake of illustration, an example is given in Figure 6.a). If we want to have information on which product is currently on the production line,we can obtain this information by implementing a radio frequency identification RFID sensor, since it is connected to PLC Logix controllers (Figure 6.b)) through a set network [30,31,32]. The control, information and monitoring of the current product packaging on the packaging section is shown in Figure 6. c, d), whereas the monitoring of products and raw materials at each stage from entry, production and shipment to the end customer isshown in Figure 6.e, f). We can achieve increased productivity and production efficiency by implementing smart sensors. We can also achieve detailed monitoring of products, as well as the visibility of the supply chain in order to make the right decisions on time. An example of monitoring certain positions in the production process by implementing smart sensors is shown in Figure 7. Depending on the production process, there are different positions for the application of smart sensors. In addition, the choice of information we are interested inwill influence the choice of smart sensor that will be placed to monitor and obtain information [31,32].

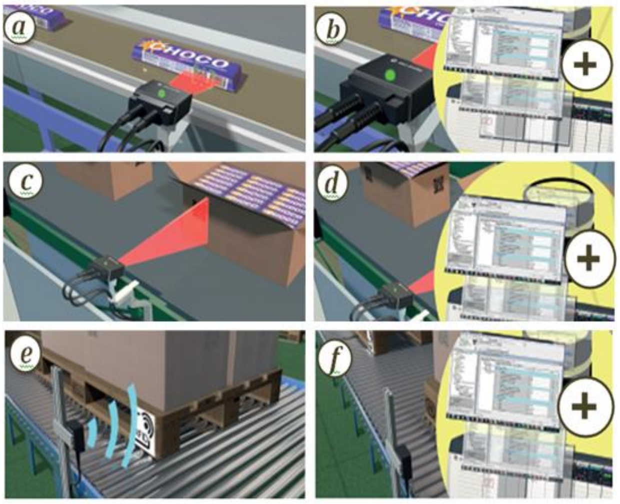


Fig. 6. Monitoring of certain parameters with smart sensors in the production process

Figure 7 shows an illustrative example in which the temperature is monitored in the production process. There is a sensor that shows that the temperature is 45 ◦C, while the second position displays the application of pressure sensor which shows a pressure of 50 bars. In the third position, there is a proximity sensor that registers the positioning of the product on the 750 mm conveyor belt, while the power signal is 500 units. At the end of the production process, a sensor for counting parts was installed, which is now active and providing information that there are 1284 units of elements.

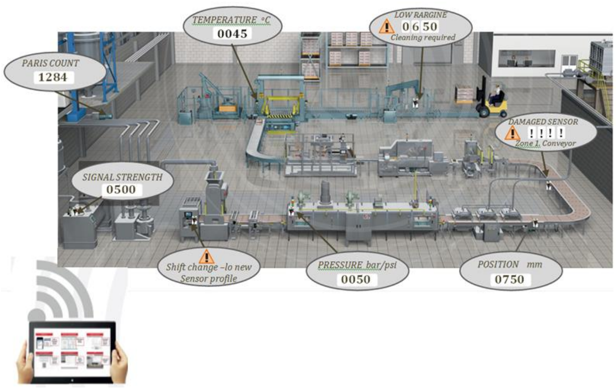


Fig.7. Mobile monitoring of production process parameters using smart sensors

Monitoring of the production process can take place on different devices, static screen or mobile device. In this particular example on the mobile device we have information about the problem on three sensors that we need to eliminate. The sensor in zone 1 is loaded on the conveyor belt, the second sensor needs cleaning, and the third sensor shows a warning that we have to change the sensor profile, i.e., we have to adjust the new sensor profile. When we have complete information given to us by smart sensors from the production process, we can act in time and eliminate errors so that the production process works normally. As we have seen in the concrete example on mobile devices in Figure 7, we can monitor the information in the production process, as well as problems on sensors that we need to eliminate. After analyzing the obtained information, we can make a decision on what actions need to be performed, such as cleaning or changing the sensor profile. In other words, we need to adjust the new sensor profile. When we have complete information given to us by smart sensors from the production process, we can act in time and eliminate errors so that the production process works normally.

3. CONCLUSION

Industry 4.0 is the one that provides relevant answers to the fourth industrial revolution. It is already present in all industries, from production to sales of finished products. By introducing technologies that form the basis of the fourth industrial revolution or Industry 4.0 such as: smart sensors, robotics and automation, big data (Big Data), Internet of Things (IoT), 3D printing, radio frequency identification (RFID), virtual and augmented reality, artificial intelligence (AI), advanced security systems, etc., we can change processes and technologies as well as the organization of production and sales. The fourth industrial revolution brings disruption to almost every industry in the world, because it has a greater impact than we think. The impact is reflected on all sectors and companies, including large, medium and small companies. Industry 4.0 relies on advances in the use and sharing of information, and has such potential to connect almost anything and everything on the web, thus drastically improving the company's business performance. Small and medium enterprises can benefit from what Industry 4.0 has to offer, because by using the technologies mentioned in this chapter, they can more efficiently process and store data, and improve the way they design, manufacture and deliver their products. Currently, small companies can compete with big companies in a way they never could before. It is impossible to implement Industry 4.0 without smart sensors. They are the ones that give the first information about monitoring parameters in the production process. Their implementation provides the company with advantages, some of which are:

- lower operating costs
- improved business communication processes
- increased productivity of companies
- access to the world economic market is expanding (wide user base)
- provides companies of all sizes with greater outsourcing opportunities (external associates)
- thanks to the availability of new communication tools the cooperation of company departments and individuals is easier
- advanced achievements, such as blockchain technology, greatly increase the security of business and personal data
- reduced downtime in the production process,
- rapid adaptation of the production process to the production of another product

As we have seen, advanced technologies that include: IoT (Internet of Things), robotics, cloud computing, smart sensors, radio frequency identification, cyber-physical systems and big data, are key in the application of the

Industry 4.0 concept, because they imply full digitalization of all production processes, as well as creating an idea about a product, product engineering, production organization, process control, and the provision of industrial services. Based on all this, we can conclude that new constructions of smart sensors will be developed in the future, and their implementation in production processes, as well as in all segments of the human environment, will increase on a daily basis.

REFERENCES

[1] Karabegović Isak, Karabegović Edina, Smart Sensors: Support for the Implementation of Industry 4.0 in Production Processes, Chapter 7. Handbook of Research on Integrating Industry 4.0 in Business and Manufacturing, IGI Global, USA, pp.147-163, (2020), DOI: 10.4018/978-1-7998-2725-2.ch007

[2] Schwab, K.: The Fourth Industrial Revolution, World Economic Forum, Geneva, Switzerland, (2016)

[3] Karabegović, I.,Kovačević, A., Banjanović-Mehmedović,L.,Dašić,P.:Integrating Industry 4.0 in Busniess and Manufacturing, IGI Global,Hershey, PA, USA, (2020) https://www.igi-global.com/book/handbook-research-integrating-industry-business/237834

[4] Chryssolouris, G., Mavrikios, D., Papakostas, N., Mourtzis, D., Michalos, G., Georgoulias, K.: Digital manufacturing: History, perspectives, and outlook, Journal of Engineering Manufacture, Proceedings of the Institution of Mechanical Engineers, Part B, pp.451-462(2009) http://dx.doi.org/10.1243/09544054JEM1241

[5] Karabegović Isak and Karabegović E., The Role of Collaborative Service Robots in the Implementation of Industry 4.0,*International Journal of Robotics and Automation Technology*,Vol.6., 40-46, (2019) (https://www.zealpress.com/;

[6] UNCTAD (2018) Technology and innovation report 2021, United Nations conference on Trade and Development; based on data from Maddison Project Database, version 2018, Bolt et al. (2018), Perez (2002), and Schwab (2013).https://unctad.org/system/files/official-document/tir2020overview_en.pdf

[7] Muller, J.M., Buliga, O., Voigt, K.I.: Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0. Technological Forecasting and Social Change, Vol.132,Iss.C, pp.2–7 (2018) DOI: 10.1016/j.techfore.2017.12.019

[8] Isak Karabegović The Role of Industrial and Service Robots in Fourth Industrial Revolution with Focus on China ,Journal of Engineering and Architecture ,Vol. 5, No. 2, pp. 110-117 , (2017) DOI: 10.15640/jea.v5n2a9 URL: https://doi.org/10.15640/jea.v5n2a9

[9] Edina Karabegovic, Isak Karabegovic, Edit Hadzalic (2012),Industrial Robot Application Trend in World's Metal Industry *Inzinerine Ekonomika-Engineering Economics,* , 23(4), 368-378 ,http://dx.doi.org/10.5755/j01.ee.23.4.2567

[10] Hermann, M.; Pentek, T.; Otto, B. Design principles for industrie 4.0 scenarios. In Proceedings of the IEEE 2016, 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, USA, pp. 3928–3937 (2016), http://dx.doi.org/10.1109/HICSS.2016.488

[11] Thoben, K.D.; Wiesner, S.; Wuest, T. Industrie 4.0 and smart manufacturing-a review of research issues and application examples. International Journal Automation Technology , Vol.11, pp.4–16 (2017) https://doi.org/10.20965/ijat.2017.p0004

[12] Karabegović,I.: The Role of Industrial and Service Robots in the Fourt Industrial Revolution, ACTE TechnicaCorviniensis-Bulletin of Engineering,UniversityPolitehnicaTimisoara,Tome XI, Fascicule 2. April 2018. Hunedoara,Romania, pp.11-16 (2018)http://acta.fih.upt.ro/pdf/2018-2/ACTA-2018-2-01.pdf

[13] Karabegović. I., Karabegović, E., Mahmić, M., Husak, E.: The application of service robots for logistics in manufacturing processes, Advances in Production Engineering & Management, Vol. 10. No. 4. 2015,Maribor, Slovenia, EU, pp. 185-194 (2015)https://www.apem-journal.org/Archives/2015/APEM10-4_185-194.pdf

[14] Karabegović, I., Karabegović , E., Mahmić, M., Husak, E.: Implementation of Industry 4.0 and Industrial Robots in Production Processes In: Isak Karabegović (eds) New Technologies,Development and Application II 2019. Lecture Notes in Networks and Systems. Springer Nature Switzerland AG 76, pp.96-102 (2020)

[15] Karabegović, I., Husak, E.: Industry 4.0 based on Industrial and Service Robots with Application in China, Journal Mobility and Vehicle,44(4), pp.59-71 (2018)

[16] Karabegović, I.: The Role of Industrial and Service Robots in Fourth Industrial Revolution with Focus on China,Journal of Engineering and Architecture, 5(2), pp.110-117 (2017)

[17] Byeong, W.A. , Jung, H. S., So-Yun, K., Joohee, K., Sangyoon, J., Jihun, P., Youngjin, L., Jiuk, J., Young-Geun, P., Eunjin, C., Subin, J. & Jang-Ung, P. (2017). Smart Sensor Systems for Wearable Electronic Devices, *Journal Polymers, 9(303)*,1-32

[18] Johan, H.H.,Frank R.R. & Gertvan H. (1994). Developments in integrated smart sensors, *Sensors and Actuators A: Physical,43(1–3)*, 276-288

[19] Karabegović I.,Husak E.,Predrag D.:The Role of Service Robots in Industry 4.0 - Smart Automation of Transport,International Scientific Journal Industry 4.0, Vo.4. Iss.6. pp.290.292 (2019) https://stumejournals.com/journals/i4/2019/6/290

[20] Andreas, S., Nikolai, H., & Tizian, S. (2018). Sensors 4.0 – smart sensors and measurement technology enable Industry 4.0, *Published by Copernicus Publications on behalf of the AMA Association for Sensor Technology*,359-371.

[21] Gary, W. H., Joseph, R. S., Peter, J. H., & Chung-Chiun L. (2010). Smart Sensor Systems, *The Electrochemical Society Interface* , *Winter 2010*, 29-34.

[22] Karabegović Isak, Karabegović Edina, Mahmić Mehmed, Husak Ermin, The Implementation of Industry 4.0 by Using Industrial and Service Robots in the Production Processes**,** Chapter 1. Handbook of Research on Integrating Industry 4.0 in Business and Manufacturing, IGI Global, USA, pp.1-30, (2020), DOI: 10.4018/978-1-7998-2725-2.ch001

[23] Randy, F. (2013). Smart Sensors, Series: Artech House Remote Sensing Library, Massachusetts, Publisher-Artech House,

[24] Clarence, W. S. (2017). Sensor and Actuators, Engineering System Instrumentation, Second Edition, 2nd Edition, Florida,CRC Press.

[25] Bunse, B., Kagermann, H., & Wahlster, W. (2017). Industrie 4.0:Smart Manufacturing for the Future, *Brochure, 20750. Germany Trade and Invest, Gesellschaft für Außenwirtschaft und Standortmarketing mbH, Berlin,* Germany.

[26] Karabegović, I., Karabegović, E., Mahmić, M., & Husak, E. (2015). The application of service robots for logistics in manufacturing processes, *Advances in Production Engineering & Management*, 10(4); 185-194.

[27] Karabegović I., & Husak, E. (2018) Industry 4.0 based on Industrial and Service Robots with Application in China, *Journal Mobility and Vehicle,44(4),* 59-71

[28] Rockwel Aotomation. (2016). Condition Sensors and Switches,Publication 836E-BR001C-EN-P, USA.

[29] Rockwel Aotomation. (2017). Get Smart,Key considerations for developing smart machines and equipment,Publication: OEM-SP019B-EN-P, USA.

[30] Rockwel Aotomation. (2016). Smart Sensors, Enabling Smart Machines for The Connected Enterprise, Publication IOLINK-BR001B-EN-P, USA.

[31] Rockwel Aotomation. (2011). Sensor Application Guide, PublicationSENS-AT001B-EN-P–May2011, USA.

[32] Rockwel Aotomation. (2016). Integrated Smart Sensors, Publication SENSOR-BR002A-EN-P, USA.

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SAFETY 4.0 - MACHINE SAFETY AND STANDARDIZATION IN INDUSTRY 4.0

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Nataša SOLDAT
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Abstract: *This paper gives a critical discussion of new trends in the field of Machine safety demanded by Industry 4.0. Industry 4.0 brings digitalization and robotization as ubiquity trend in the machinery, thus affecting all spheres of human life and work. These processes dictate the needs for fast adaptation, as well as the opening of a new field to which special attention should be paid, concerning the impact of Industry 4.0 on machine safety and human-machine interaction, so-called Safety 4.0. Safety 4.0 could be on one side considered as a task to keep worker safety, as well as to improve accident prediction and prevention. On the other side, the new devices and technologies, favorized by Industry 4.0, give new possibilities to significantly improve health and safety within human-machine relationship. In accordance with the already established system of standardization, adjustment is inevitable in this area in order to cover all of these aspects of Safety 4.0. The review of the current standardization in the national and EU level in this field, as well as the ongoing procedures for standards under development and amendment related with the Machine safety in the framework of Industry 4.0 is discussed in this paper.*

Keywords: *safety 4.0; Industry 4.0; standardization; machine safety*

1. INTRODUCTION

In recent years, a growing number of scientists and engineers have devoted their attention to research into the impact of Industry 4.0 paradigm on various spheres of human life and work. Although Industry 4.0 started as an idea of a new industrial revolution [1], which is primarily based on the robotization and digitalization in manufacturing and all processes that accompany it, the concept of Industry 4.0 has extended its impact to all spheres of human work and life [2, 3]. The latest articles published about Industry 4.0 are dedicated to its transformation from a new industrial revolution to a new human working and living environment, lead to the conclusion that it is necessary to study all of the aspects of the human life from the viewpoint of the development of new industry concepts. Vaidya et al. [4] concluded that "The manufacturing industries are currently changing from mass production to customized production, while the rapid advancements in manufacturing technologies and applications in the industries help in increasing productivity." Gorecky et al. [5] recognized the new challenges brought by Industry 4.0, and concluded that: "The development of Industry 4.0 will be accompanied by changing tasks and demands for the human in the factory. As the most flexible entity in cyber-physical production systems, workers will be faced with a large variety of jobs ranging from specification and monitoring to verification of production strategies. Through technological support it is guaranteed that workers can realize their full potential and adopt the role of strategic decision-makers and flexible problem-solvers." Badri et al. [6] expressed their major concern about the impact of Industry 4.0 as the predominant reality on the management of occupational health and safety (OHS). They presented the following questions: "In the midst of this new and accelerating industrial trend, are we giving due consideration to changes in OHS imperatives? Are the OHS consequences of Industry 4.0 being evaluated properly? Do we stand to lose any of the gains made through proactive approaches? Are there rational grounds for major concerns?" In this article [6], Badri et al. actually opened the problem of new viewpoint on Industry 4.0 and increased productivity it brings, by considering the important changes in human and working environment. Bragança et al. give a brief overview [7] for the part of this problem, and consider how the collaborative robots can be used to support human workers in Industry 4.0 manufacturing environments. Also, they highlighted that, although the collaborative robots bring many advantages and enable more efficient product systems by supporting workers with both physical and cognitive tasks, on the other hand, human–robot interaction might also have some risks if human factors considerations are not well thought throughout the process. They concluded that the role that humans have been playing so far in a manufacturing environment is rapidly changing. In new conditions, human workers will have to adapt to these new systems by acquiring and improving a set of skills that have sometime been neglected until nowadays.

In this framework, in addition to social challenges and adjusting of the education programs, it is also necessary to implement changes in the Environmental Health and Safety (EHS) management. Safety could be recognized as one of the main challenges within Industry 4.0 development and implementation [8, 9]. Consequently, a complete set of measures needs to be taken in order to adapt the existing regulations and standards in the field of machine safety. This paper deals with this issue, and discusses the aspects of Safety 4.0 that are opening up within the application of Industry 4.0, as well as the necessary development of new and adaptation of existing technical standards in order to fulfill the safety requirements in the conditions of inevitable changes carried by new industrialization.

2. SAFETY 4.0 – MACHINE SAFETY IN INDUSTRY 4.0

2.1. Basics of EHS 4.0 management

The Environment, Health and Safety (EHS) management has a main role to ensure people and the environment stay safe, while the manufacturing processes work smoothly. The EHS management is faced with new challenges during last years as a result of the processes caused by Industry 4.0 implementation. Industry 4.0 use of computer-cyber systems and set the people connections, machines, and data on new level. Key technology advances including the contemporary technologies such as sensor-equipped devices, cloud computing, mobile apps, and Big Data analytics, enable the overarching trend of the Industrial Internet of Things (IIoT) [10]. But, Industry 4.0 also generate certain disruptions in the industries, as companies transform business models, processes, and performance. Along with new opportunities to optimize performances, this resulted on new business and operational risks. These circumstances demand certain changes and adjustments in EHS management, which can be defined as EHS 4.0.

The EHS 4.0 can be defined as [11]: “EHS 4.0 is a term which defines the current state of safety technology and processes and the specific ways it is advancing with the help of digitalization. Bussey [10] deals with the definition of the Environmental Health and Safety 4.0 (EHS 4.0). He explains the basics of the EHS 4.0 as follows: “EHS 4.0 provides the means to harness today’s technology to enable fresh approaches to EHS management. EHS 4.0 is not a technology per se but rather is enabled by technology innovations. It’s a framework of capabilities that can help organizations go beyond traditional EHS management to transform how they manage performance improvement.”

The EHS 4.0 can be presented and described over seven dimensions, Fig.1 [10]:

- → Strategic;
- → Systematic;
- → Risk-based;
- → Connected;
- → Smart;
- → Agile;
- → Engaged.

Although this is not a new technology, it is clear that the role of EHS 4.0 is very important in building a safety working and living environment, which aims healthy and happy individuals.

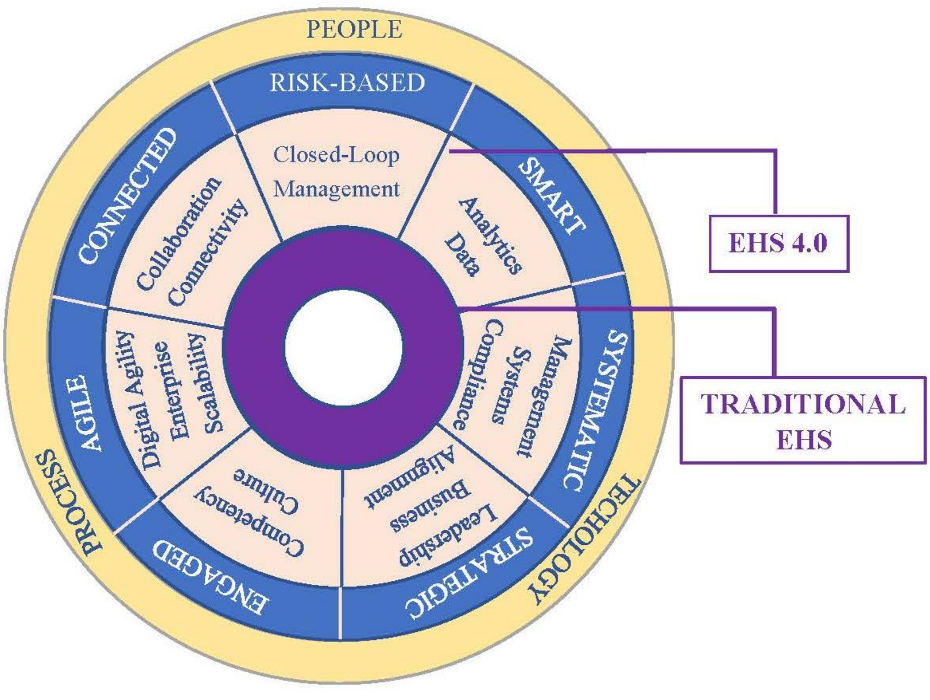

Fig.1. The seven EHS 4.0 dimensions, [10]

2.2. Safety 4.0 – main postulates

One of the main parts of the EHS 4.0 is Safety 4.0. Some authors start with the standpoint that the EHS 4.0 can be defined also as Safety 4.0 [11], considering that safety is the basic and most important part of the Environment, Health and Safety concept.
The driver of the 4th industrial revolution is technology, but it is obvious that the implications go much deeper [12]. As early as 2013 Titus [13] noticed new trends in the industry development and asked a question "Is machine safety included?". He recognized that: "The industry experts believe that we could well be in the midst of the fourth industrial revolution, and that the basis for this belief is a smart industrial intranet able to connect machines and products using technologies like wireless and radio frequency identification (RFID) to gain knowledge and improve efficiency without human intervention." He also had the fears about the new industrial revolution impact on the machine safety: "It's only just recently that machine safety was allowed to leave hard wired guarding applications and re-join the automation curve that began in the 1970s. Now, machine safety is a part of electronics and IT arena of the third industrial revolution. Otherwise, machine safety would still be relegated to the second stage. But, since machine safety for many applications is now part of the platform for launching into the fourth industrial revolution, is it included? Or, will machine safety be left behind again, such as in the transition to the third industrial revolution?" From that time until today, in less than 10 years, this has become a reality, and we face almost every day the challenge of the 4th industrial revolution.
In nowadays industry progress, we need to recognize the fact that the changes in technology without accompanying strategic and cultural changes can cause more problems than they solve. So, the changes in the processes and legislative that define measurements for providing high level of safety need to be changed and improved.
Some of the conclusions of the recent Campbell Institute Symposium of the National Safety Council [12] is that "The first step is to become more familiar with emerging technologies for safety and more generally for other purposes that may support safety efforts. New products are being developed at an incredible pace and safety professionals will find they need either more time, exposure (conferences and workshops, etc.), professional help from the IT department or even a dedicated safety technician. New digital equipment ranges from drones and robots to wearables for workers, proximity sensors for vehicles and even smart PPE."

3. STANDARDIZATION IN INDUSTRY 4.0 AND SAFETY 4.0

3.1. Standardization in Machine safety

Many authors and national institutions all over the world already deal with the problem of standardization in Industry 4.0 and Safety 4.0. Although they have analyzed different standpoints within this problem, all agree that it is necessary and important to pay special attention to this problem.

The following initiatives are already underway at the international level within the process for improving standardization in this field [14]:

- ISO/TMBG/SMCC Smart Manufacturing Coordinating Committee. The highest decision-making body of the ISO, the Technical Management Board (TMB), has convened an expert group to shape a response to the use of Standards across the ISO, including around an agreed scope of what constitutes smart manufacturing.
- The International Electrotechnical Commission (IEC) has established a Systems Committee on Smart Manufacturing. This seeks to "provide coordination and advice in the domain of Smart Manufacturing to harmonize and advance Smart Manufacturing activities in the IEC."
- Joint Technical Committee (JTC) 1, which coordinates key ICT-related standardization activities between the ISO and IEC, has already turned its mind to these issues. One key area is 3-D printing and scanning, which is underpinning advances in everything from med-tech to construction. Working Group 12, within JTC 1, is currently exploring 3-D Printing and Scanning, with experts nominated from member countries to shape future standards in these areas.

There are also a range of other Committees responsible for Standards development in specific discrete areas relevant to powering Industry 4.0. These include ISO/TC 299 (Robotics) and ISO/TC 184 (Automation systems and integration), for example.
The interesting analysis in this area from the aspect of functional safety, which can be defined as a part of safety is introduced by Tom Meany [15], dealing with confidence that a system will carry out its safety related task when required to do so. He based his analysis and discussion on the IEC serial of standards [16, 17], started with the basic functional safety standard - IEC 61508. Also, he has given a discussion how the IEC standards are relating with complementary ISO standards, in first place through the consideration of the changes and adjustments to Industry 4.0 demands of ISO 10218 [18], standard covering the safety requirements for industrial robots including cobots, as well as ISO 13849, which considers the safety requirements of the safety-related parts of control systems.

3.2. Ongoing standardization in Safety 4.0

The processes connected with the development new standards and modifications of the existing standards, which is related with different aspects and implementations of Industry 4.0, are very intensive at the level of the international standardization, Fig.2.
The field of machinery safety, which are already a subject of the special attention during last few decades, need to be considered as an important aspect in these processes. The holders of the mandatory safety rules, which have been incorporated into a large number of national regulations, including Serbian one, have noticed in recent years the urgency for appropriate modifications of the current

Directive on machinery (Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006) in the context of Safety 4.0. The amending the Directive on machinery by the TC199 Machine Safety Technical Committee within the ISO (the International Organization for Standardization) is underway [19, 20] Also, Technical Committee TC199 is working to adopt new standards of critical importance for safety in Industry 4.0 [21], such as ISO/DIS 21260 "Safety of machinery - Mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons" [22], which is adopted in collaboration with ISO/TC299 (Robotics). Technical Comity ISO/TC199 has also issued technical report IS/TR 22100-4 "Safety of machinery - Relationship with ISO 12100. Part 4: Guidance to machinery manufacturers for consideration of related IT security (cyber security) aspects" [23]. In accordance with the discussion given in the previous part of this article, the basic requirements and standards related with the European Framework Directive on Safety and Health at Work (Directive 89/391 EEC) must also be considered within the possible implications of the application of Industry 4.0 to occupational safety and health [20].

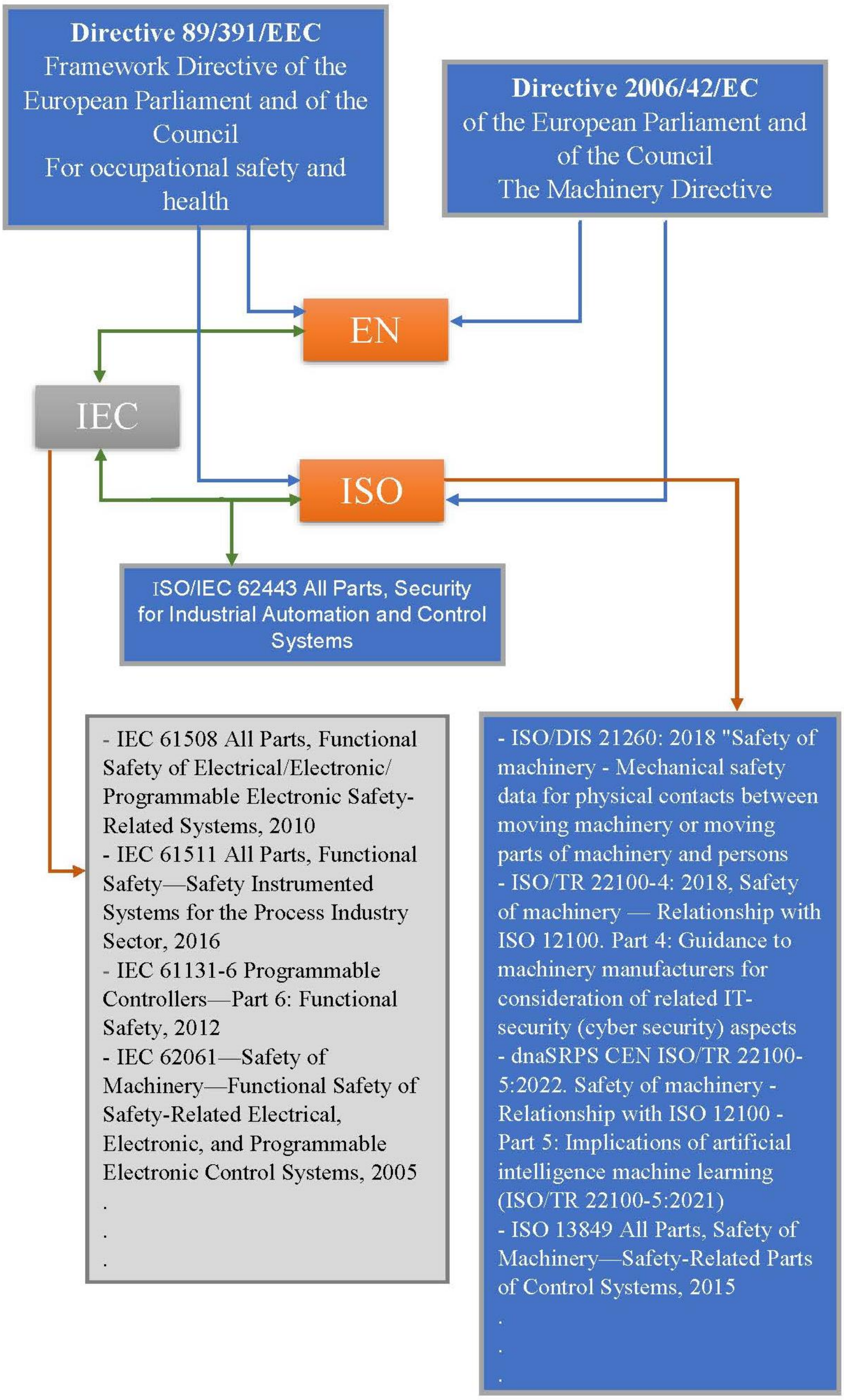

Fig.2. The Ongoing standardization in Safety 4.0

Some of the standards, analysed and mentioned by authors during last few years, are already adopted for implementation. The processes of standards' modifications are ongoing in different technical groups of the international standardization associations. The Institute for standardization of Serbia is involved in these processes, with a role of a member of The European Committee for Standardisation (CEN). This institution works actively on adopting of new ISO, IEC and EN standards at the national level, through few technical committees (TCs). One of these technical committees is TC Safety of machinery, which scope is: Safety machine and ergonomics, defined by the basic principles of machinery safety, terminology, methodology, and security aspects of the machines from different areas of production [24].

One of the newest standards adopted from the discussed group at the national level is dnaSRPS CEN ISO/TR 22100-5:2022. Safety of machinery - Relationship with ISO 12100 - Part 5: Implications of artificial intelligence machine learning (ISO/TR 22100-5:2021) [25] In accordance with the given scope of this standard: "This document addresses how artificial intelligence machine learning can impact the safety of machinery and machinery systems. This document describes how hazards being associated with artificial intelligence (AI) applications machine learning in machinery or machinery systems, and designed to act within specific limits, can be considered in the risk assessment process. This document is not applicable to machinery or machinery systems with AI applications machine learning designed to act beyond specified limits that can result in unpredictable effects. This document does not address safety systems with AI, for example, safety-related sensors and other safety-related parts of control systems."

4. CONCLUSION

Industry 4.0 is in nowadays the leading technology and philosophy. Its main characteristics are implementation of smart technologies, in first place the internet and artificial intelligence. The primarily aims are to advance productivity, efficiency, and cost reduction. Although this technology revolution has the improving of worker health and safety as one of the main goals, the impacts that Industry 4.0 produces at the human and working environment, as well as at the all spheres of the people life, demands comprehensive actions. These include the changes necessary to create a safe, connected workforce, mitigating risks while improving work processes, full integration and real-time connectivity between management, operations, and the individual worker. That defined the main goals of the Safety 4.0, discussed in this paper. One of the main parts of this activity is the development of appropriate international standardization framework. The initiatives for this process are already initiated at all standardization institutions and levels. The analysis presented in this paper discusses the main current steps and flows in this framework, as well as highlights the necessity of new efforts within Safety 4.0 development.

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REFERENCES

[1] Sachin, S. Kamble, Angappa Gunasekaran, Shradha A. Gawankar: Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives, *Process Safety and Environmental Protection*, Vol. 117, pp. 408-425. doi: 10.1016/j.psep.2018.05.009, 2018

[2] Safety 4.0® White Paper, GOARC, www.go-arc.com, Accessed on: 2022-03-16

[3] Murray, D.: The Effect of Industry 4.0, Efficiently Increase Production While Improving Safety, Schmersal USA, 2020

[4] Vaidya, S., Ambad, P., Bhosle, S.: Industry 4.0 – A Glimpse, *Procedia Manufacturing*, Vol. 20, pp. 233-238. doi: 10.1016/j.promfg.2018.02.0342018, 2018

[5] Gorecky et al.: Human-Machine-Interaction in the Industry 4.0 Era, *12th IEEE International Conference on Industrial Informatics (INDIN)*, pp. 289-294, 2014

[6] Badri et al.: Occupational health and safety in the industry 4.0 era: A cause for major concern?, *Safety Science*, Vol 109, pp. 403–411, 2018

[7] Bragança, S., Costa, E., Castellucci, I.: A Brief Overview of the Use of Collaborative Robots in Industry 4.0: Human Role and Safety, In: *Arezes et al. (eds.), Occupational and Environmental Safety and Health, Studies in Systems, Decision and Control 202*, doi: 10.1007/978-3-030-14730-3_68, 2019

[8] Atanasovska, I., Tomovic, R., Mitrovic, R., Soldat, N.: Contribution to the development of laboratory 4.0 for rolling bearings testing, *Application of Industry 4.0 – an Opportunity for a New Step Forward in all Industrial Branches, Sarajevo, 14th April, 2022, BiH, Proceedings, Special Editions of the Academy of Sciences and Arts of Bosnia and Herzegovina, Department of Technical Sciences*, Vol. 20, Publisher: Academy of Sciences and Arts of Bosnia and Herzegovina, Editor: Isak Karabegović, doi: 10.5644/PI2022.202.23, pp. 93-102, 2022

[9] Forcina, A., Falcone, D.: The role of Industry 4.0 enabling technologies for safety management: A systematic literature review, *International Conference on Industry 4.0 and Smart Manufacturing*, *Procedia Computer Sceince*, Vol 180, pp. 436-445, 2021

[10] Bussey, P.: Beginners Guide to EHS 4.0: The Seven Dimensions to Overcome Challenges and Seize Opportunities, https://blog.lnsresearch.com/ehs40, 2017, Accessed on: 2022-03-16

[11] What is EHS 4.0 or Safety 4.0?, https://www.safer.me/ blog/what-is-ehs-4-0/, 2019,Accessed on: 2022-03-16

[12] Mathis, T.: Safety 4.0: Updating Safety for Industry 4.0,https://www.industryweek.com/operations/article/22025443/safety-40-updating-safety-for-industry-40, 2018, Accessed on: 2022-03-16
[13] Titus, J.B.: Machine Safety: Industry 4.0 and how it could impact machine safety, https://www.controleng.com/articles/machine-safety-industry-4-0-and-how-it-could-impact-machine-safety/, 2013, Accessed on: 2022-03-09
[14] Standards, Norms and Reference Architecture https://i4amf.aigroup.com.au/streams/standards-guidelines/ , Accessed on: 2022-03-16
[15] Meany, T.: Functional Safety and Industry 4.0, https://www.analog.com/en/technical-articles/functional-safety-and-industry-4.0.html Accessed on: 2022-03-16
[16] IEC 61508 All Parts, Functional Safety of Electrical/Electronic/ Programmable Electronic Safety-Related Systems, International Electrotechnical Commission, 2010.
[17] IEC 62061—Safety of Machinery—Functional Safety of Safety-Related Electrical, Electronic, and Programmable Electronic Control Systems. International Electrotechnical Commission, 2005
[18] ISO 10218-1, Robots and Robotic Devices—Safety Requirements for Industrial Robots—Part 1: Robots. International Organization for Standardization, 2011
[19] Mitrovic, R., Atanasovska, I., Soldat, N., Miskovic, Z.: New Trends in Machine Design within Industry 4.0 Framework, *AMP 2020, LNME*, pp. 227-238. doi: 10.1007/978-3-030-46212-3_16, 2020
[20] Negre, T.: Safety 4.0 - Smart Machines & Factories, https://smartmachinesandfactories.com/news/fallstory.php/aid/173/Safety_4.0.html, Accessed on: 2020-01-31, 2017
[21] Steiger G.: New digital production technologies - Challenges for machinery safety standardisation, https://www.euroshnet.eu/fileadmin/Redaktion/Presentations/1_Steiger_Digitalisation_in_the_machinery_sector-implications_on_safety.pdf, Accessed on: 2020-01-31
[22] ISO/DIS 21260: 2018. Safety of machinery — Mechanical safety data for physical contacts between moving machinery or moving parts of machinery and persons
[23] ISO/TR 22100-4: 2018, Safety of machinery — Relationship with ISO 12100. Part 4: Guidance to machinery manufacturers for consideration of related IT-security (cyber security) aspects
[24] M199, Safety of machinery, https://iss.rs/en/committee/show/9111
[25] dnaSRPS CEN ISO/TR 22100-5:2022. Safety of machinery - Relationship with ISO 12100 - Part 5: Implications of artificial intelligence machine learning (ISO/TR 22100-5:2021)

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MICRO AND NANO TECHNOLOGIES (MNTs) IN INDUSTRY 4.0 COMMUNICATION SYSTEMS

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Abstract: *This paper presents some solutions used in communication systems of Industry 4.0 context that are based on micro- and nano-technologies. There is a significant need for miniaturized multifunctional components that can be incorporated within different system elements in an existing industrial production system, without altering the basic system function. A range of micro- and nano-devices have been studied to serve as the foundation for development and deployment of sensor network that simultaneously can provide some other functions, like sensing, actuation and/or energy harvesting. However, no high amount of such devices has been incorporated in real industrial systems so far. Big data in Industry 4.0 strongly relies on a possibility for real-time data collection, which is based on sensor network. Physical positioning of such network throughout the production facilities can be a very challenging task for companies. Advanced multifunctioning sensors are usually based on utilization of advanced materials very often incorporating micro- and/or nano-materials. Fiber-optic sensors are widely used and commercialized components used in quality control in civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials or structural health monitoring. Advantages of miniaturized fiber-optics sensors are: smaller size, lower power consumption, higher sensitivity and faster response.*

Keywords: *microsensors; nano-enabled sensors; fiber-optic sensors; energy harvesting; quality control*

1. INTRODUCTION

Industry 4.0 can be considered as digitalization of production, managerial, and administrative processes and it is based on 4 principles: interconnectivity, information transparency, technical support, decentralized decision making [1]. Interconnectivity is based on connecting production equipment, measurement equipment, sensor/monitoring systems, support systems with computing systems and smart devices [1]. This way all collected information can be software processed and available to the system users in a form of simple, precise and real-time information[1].

For some quality processes sensing equipment can be expensive, but even bigger challenge can be sensor integration. For some processes conventional sensors cannot be integrated due to its size (for small systems like proton-exchange membrane (PEM) they are too big), or because they cannot withstand the environment (temperature, acidity, moisture, pressure, etc.). Micro and nano technologies (MNTs) provide wide range of sensors on micro and nano level which can be less pricy and more precise than conventional sensors. Micro and nano sensors have advanced in the recent years and are capable of sensing/monitoring many different characteristics, harvesting energy, and interacting with micro and nano environment. This paper presents micro and nano-based sensors which can be applied to sense:

- Different gasses,
- pH value,
- Moisture content,
- Humidity,
- Shape changes,
- Strain,
- Acoustics,
- Temperature,
- Pressure,
- Vibration characteristics,
- Voltage,
- Current,
- Flow distribution,
- Ions.

Large number of micro and nano sensors can be produced relatively inexpensively. This means that a number of these small sensors can be deployed to provide measurement data for a single process. Human brain can process and understand only limited amount of data [2]. To understand large amount of measurement data 'Big data' analytics can be applied. Big data analytics is a method of collecting, sorting, understanding and processing large amount of data [2]. Chaotic systems are often unpredictable and sensitive to initial conditions, so when there is a lot of data, unlike human brain, Big data analytic system can process them and predict the outcome [2]. Big data analytics can be successfully paired with MNT sensing systems for the purpose of industrial monitoring of parameters and predicting of the outcome in the production, maintenance, health and safety, and quality control processes.

Optic systems are superior in comparison to metal components regarding the data transfer and infrastructure longevity [3]. Optic systems are not prone to oxidation, they have low attenuation, and electromagnetic forces do not interfere with data transfer [3].

2. IMPLEMENTATION CHALLENGES OF INDUSTRIAL INTERNET OF THINGS (IIoT)

MNT sensors can be very successfully applied as a part of industrial monitoring systems. Industrial equipment generates a lot of data, second by second, measurement by measurement. Industry 4.0 steers the industry leaders to strive for the great level of data availability and accessibility [2]. Industrial Internet of Things is a term which describes interconnection of industrial equipment and cyber systems [4]. In order to provide all of the needed information in a real time manner, regardless of the location of the person which requires data, IIoT must be utilized [5]. Sometimes the amount of measurement data is so large that it would be impossible for an expert to understand the meaning behind the data set. Number of methods have been studied in relation to Big data analytics and its structures that would enable comprehensible and usable information [5]–[7]. In case of industrial production process, like welding operation, one could use MNT sensors to track changes in temperature, voltage, arc current, pressure, welding head speed and position, welded object shape changes and many more. Every tenth of a second (or faster) a measurement can be updated, meaning that Big Data can be used to structure the data and IIoT approach can provide data storage, accessibility and availability. However, for a prediction of welding defects, only comprehensive description of the process parameters, within the specification limits, can be currently used. If the process parameters are within the specification limits and some defects still occur, artificial intelligence can be applied to find the link between the process parameters and the outcome [1]. In order to apply this kind of solution, data is required. Available data can be characterized based on the following criteria [8]:

- Amount of available data,
- Dynamics of data creation and upload,
- Diversity of the data,
- Data accuracy,
- Form of the data.

In case of insufficient amount of data, AI predictive system cannot be calibrated for all of the possible variations and defects. This will lower the accuracy of the AI algorithm [9]. If measurement data is created very fast, one after another, but uploading to the system takes a lot of time, or the system waits until it reaches 100 measurements to upload the data, AI might not have enough time to make a decision before releasing the part to the next station. If data input is done from multiple sources or data is in different forms, such as: different file extensions; one measurement is in millimeters and the other in microns; a part of measurement data is written in paper only; some of the data is only manually downloadable from the machine or via USB drive transferred to the system, many difficulties can occur, or additional steps in data preparation might be required. Sometimes the laboratory tests results are only written in paper, stored in the self-files, this making the AI integration more difficult. Sometimes, it is impossible to match the process parameter data with test result data. There must be a link between the two, like a serial number or similar, which might not be collected during the laboratory test, or the equipment is not saving historical data, and process parameters have only a time label but are not linked to the serial number.

Significant challenge of the 4th industrial revolution is lack of skilled experts for integration of AI solutions. Another challenge in the application of AI solutions is a choice of the appropriate algorithm [10]. To have a functional system, AI method must be matched with the used data, and the desired task. There are many methods which can be applied in predictive AI systems, such as [9]:

- Taguchi method,
- Response surface method (RSM),
- Artificial neural network (ANN),
- Genetic algorithm (GA),
- Fuzzy logic systems,
- Adaptive neuro-fuzzy inference systems (ANFIS),
- Particle swarm optimization (PSO).

For the small and medium enterprises (SMEs) it is not economically viable to employ Data Analyst or an AI expert. Researchers have analyzed a solution which can be used by non-experts. The idea is to choose one of the of-the-shelf solutions and make the process faster and easier [10].

Another challenge in the Industry 4.0 transformation for the SMEs, especially if the company is old and already equipped with the machinery, besides the IT knowledge, willingness and readiness for the Industry 4.0, is the advanced technology, which can be very expensive. Some recent studies proved that integration of inexpensive sensors in the older machine systems can provide very positive results [11], [12]. For the improvement of safety and maintenance performance within SMEs, together with their transformation to smart factory, researchers applied sensor network, IIoT, combined it with a deep learning algorithm and digital twin approach [11]. Even though the investment resources, and the implementation time were very limited, it was proved that it is possible to retrofit an old plant and make it a smart one [11].

3. OPTIC SYSTEMS

In order to meet the requirements of time sensitive applications (for Industry 4.0 and 5G fronthauling), networks must be trustable, highly reactive and jitter free [13]. The goal of fifth generation (5G) networks is to cover wide range of networking cases: from ultra-low latency applications used in sensor networks (or the Internet of Things in general) to standard mobile access [13]. To decrease the latency due to physical propagation of the signals, new end-to-end architecture is required [13].

Since the light is one of the main carriers of information in communication, aim of many studies is to improve its efficiency. Orbital angular momentum (OAM) has recently become researched as degree of freedom for multiplexing data in free space, at nanoscale and optical fibers [14]. Downside of optical free-space communication using OAM multiplexing is that it suffers from scattering caused by microparticles in the atmosphere [14]. Gong et al. demonstrated transmission of color and grey images where scattering conditions were at error rate of <0.08%, which may be step forward in high-performance optical communication [14].

Modern large-scale networks rely on fiber optic networks, mainly due their big transmission capacity [3]. Present-day local computer networks use optical fiber and radio-link as dominant medium, while networks based on copper cabling are decreasing [3]. This is due to a lower security, since copper cables can radiate energy in an unpredictable manner [3]. Radio-links provide signals radiated by means of antennas which results in better secured information [3]. However, interference still presents problems. With fiber-optic transmission such problems are solved since there is no unwanted emission which would be easy to capture [3]. On the other hand, one of the issues is connection between fiber-optic cables and fiber optics systems and devices [3].

Microwave (MW) components and Reconfigurable and tunable radio frequency (RF) are also studied. For multifunctional tasks in wireless communication systems, reconfigurable microstrip filter–antenna combinations were developed. In order to reduce cost of wireless system and number of components, those devices can be used [15]. It achieves changes in the performance with electronic tuning techniques and such structures are in high demand with development of 4G and 5G applications [15]. Tu et al. demonstrated that antennas with integrated reconfigurable filters can provide radiation properties of antenna while suppressing interference [15].

Miniaturization of optical systems (for imaging and sensing) have become very popular trend, especially in biomedical application, like endoscopic and wearable medical devices [16]. New development of bio-optical systems is achieved through a metasurface-based flat lens (metalens) [16]. MBBs (meta building blocks) have function of subwavelength-spaced scatterers [16]. When MBBs' size, position and shape are tuned, lot of lights basic properties (like: polarization, focal points, phase) can be controlled in high-resolution imaging and sensing [16]. For example, conventional refractive lenses (e.g. in telescopes and microscopes) are usually designed in different shapes, more expensive and bulkier, and require sophisticated fabrication processes (molding, polishing, diamond turning) [16]. On the other hand, phase profile of meta-lens can by modified with MBBs, and with advanced micro-machining processes can be mass produced [16].

Fiber-optic sensors are widely used and commercialized components in areas like: large civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials and structural health monitoring [17]. Micro-structured optical fiber sensors represent micro-machined and micro-manipulated fiber sensors or microfibers such as tapered fiber structures [17]. Advantages of miniaturized fiber-optics sensors are: smaller size, lower power consumption, higher sensitivity and faster response [17]. There are many different fabrication methods, but one of the frequently used is heating and stretching technique for creation of long fiber taper [17]. Section of standard single mode fiber (SMF) is stretched two linear translation stages while small sector of the fiber is heated by hydrogen gas flame [17]. Whole process is precisely controlled by the computer on the submicron level [17].

Fiber-optic sensors are also often implemented into smart materials as a sensing technology. They can be embedded during the liquid phase of the composite smart material manufacturing process. In polymeric materials or concrete, temperatures rarely exceed 100°C, but in metallic materials, it can reach values above 1000°C- which creates risk of damaging sensor [18]. To avoid such thing, number of methods rely on deployment of metallic coatings which can protect optical fiber during embedding process [18]. Grandal et al. proved that advanced manufacturing brazing process can be used for embedding fiber optic sensor into Tin alloy (SnSb8Cu4) coated ST52 steel metals. Metallic coating for optical fiber protection, used in this technique, could be Ni or Cu. Coating can be 300 μm thin for 2000W laser brazing power and 300 μm for 1500W-1800W (although coatings up to 237 μm were embedded with minimal transmission loss on the fiber) [18]. Other techniques can be based on ultrasonic welding, selective laser melting, manual TIG method etc. [18].

Gallium arsenide (GaAs) is material widely used in the fields of optoelectronics and microelectronics for devices in fiber-optic communication, cable television, vehicle navigation, smart devices in telecommunication and semiconductor light-emitting diodes [19]. It is semiconductor material with advantages, in comparison to silicon, like higher electron mobility, higher temperature resistance, wider bandgap [19]. On the other hand, it has lower values of fracture toughness and elastic modulus which makes it much harder to machine [19]. One of the solutions is implementation of Atomic Force Microscope (AFM) tip-based nanomachining [19]. It is low-cost solution to perform flexible direct writing on a nano-level in single pass in different conditions, like ultra-vacuum, liquid and low temperature or high temperature [19]. This method is applied in creation of nanodots, nano lines, two-dimensional and three-dimensional nanostructures like, for example, hemisphere cavity for light –emitting diodes quantum devices on the GaAs substrate [19].

Sapphire (α-Al2O3) is monocrystalline material with excellent optical, chemical, physical and thermal properties [20]. This makes it good material for LED substrates, laser amplifiers, optical fiber sensors, windows fields. On the other hand, its limited fracture toughness, high hardness and high brittleness are rising prize of production of low-damage sapphire surface [20]. Micro cutting with assistance of ultrasonic elliptical vibrations is technique proven to be effective in processing such material [20]. Degree of cutting groove damage as well as subsurface cracks have lower values for ultrasonic assisted micro cutting, in comparison with conventional cutting [20]. Wang et al. demonstrated in their experiment that width of defects in vibrational micro cutting is 53 µm and in traditional cutting 81 µm [20]. At the same time, average cutting speed is higher and cutting force lower for ultrasonic assisted process [20].

4. POSSIBILITIES OF MICRO AND NANO TECHNOLOGY IN INDUSTRY 4.0

Industry 4.0 concept of the distributed condition monitoring in manufacturing plants is based on the sensor network located throughout the factory and incorporated within the IIoT communication architecture (usually supported by wireless and cloud technologies), as shown in Fig. 1. Advanced communication network is usually based on optic fiber technology. Optic fibers are multifunctional components, with wide application potentials. Their most common industrial applications are data transfer and sensing/ monitoring [17]. Fiber-optic sensors are small, reliable, long lasting (low oxidation), low attenuation, optical signal is not influenced by electromagnetic waves, and they can transmit signals over a great distance [17]. These features open wide variety of possibilities for industrial application. They can be integrated into many processes for continuous monitoring and quality control. Some of the sensing applications provided by Xu et al., 2017 are: detection of hazardous materials, volatile gases, pH value, ions, humidity, and many more Xu et al., 2017. Combination of the precise, continuous measurement in industrial process with Big Data analytics and AI algorithms can constitute very reliable quality control system and predictive system.

For the sensing applications, where the shape change detection of some object is required, such as aircraft wings, robotic joints, critical springs, fiber-optic sensors could provide a great solution. Solution based on helical twisted structure shows very promising results [21]. Its structure allows it to detect directional torsion and vector bending, with the possibility to eliminate influence of strain and temperature comparing wavelength change in the side and the central core [21]. This can be applied on both micro and macro level, and it presents great application potential for the equipment health monitoring and maintenance risks. It is possible to incorporate this solution also in the quality control for many different processes.

One of possible solutions in the Carbon Capture and Utilisation Systems (CCUS) is storage of collected CO_2 in the dried oil wells. Many potential risks were analysed due to potential of seismic changes. In order to avoid potential risks, researchers analysed application of fiber-optic sensor that, over its entire length, could detect changes like: strain, acoustics, temperature, pressure and many more [22]. Monitoring of these parameters could be applied to many industrial processes, such as gas and liquid storages, filling, pressing/stamping, compressed air production, and many more.

Successful experiment was done with the helicopter rotor blade, and monitoring of the blade dynamics. Optical fiber Bragg grating, and direct fiber optic shape sensing monitoring systems proved to be capable of detecting the blade shape change, frequency and vibration characteristics [23]. Same method could be applied for quality control tests during production of rotors, turbines, wipers, wings, spoilers, etc.

Sensing changes in humidity and temperature can be crucial for solid wood furniture industry i.e., solid wood components can vary in length a couple of centimeters per 1 meter when ambient humidity change. Food processing and storing is also very sensitive to temperature and humidity changes [24]. It was proved that changeable length and diameter (CLD) solution are very capable of sensing temperature and humidity changes [24]. If lumber is cut in one building, planks shaped in the second, sanded in the third, and assembled in the fourth facility, significant dimensional discrepancies may occur if the humidity/temperature changes. Network of sensors can be linked to IoT with a protocol that starts water spraying if humidity is low, or heating if it is high.

Rayleigh scattering based optical-fiber sensors are successfully used in lithium-ion battery internal temperature measurement since they can operate even when submerged in electrolyte [25]. Their small size and robust design makes them suitable candidates for the task [25]. Batteries are one of the components with the highest risk in the electric vehicles (EVs). With EVs on the path to become the primary mean of transportation, battery management systems have become very important research topic.

Micro electro mechanical system (MEMS) was utilized in order to produce integrated sensor for lithium ion batteries [26] that can monitor voltage, current, and temperature, with short response time.

Industrial waste water management and mitigation is one of the most important topics for the Health and Safety representatives. Detection of toxic or hazardous substances in the released waste water is very important, such as presence of the arsenic in the water [27]. Many possibilities have been enlightened with the advances in the field of micro motors, and more recently nano motors [28]. Their application possibilities are not investigated nearly enough. They are most usually propelled by some electrical or chemical energy source. Recent researches show that there is a great potential to use renewables to power micro and nano motors, such as wind, solar, light and sound as an external energy source [28].

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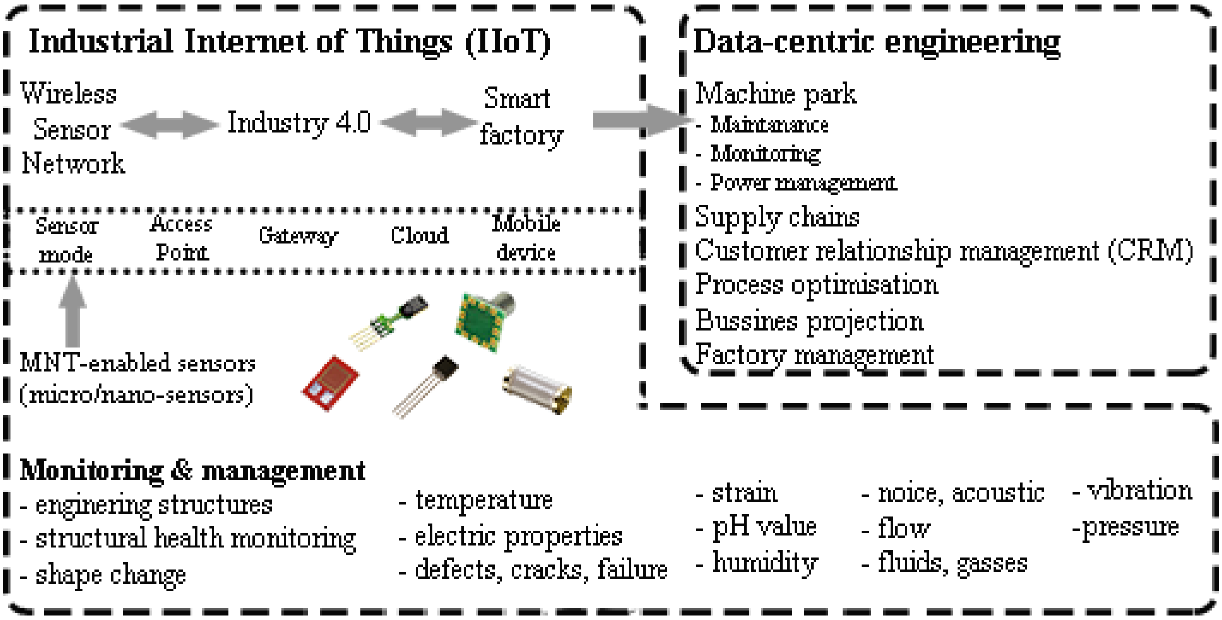

Figure 1 Schematic view of the sensor network role in distributed condition monitoring within the IIoT communication architecture supported by the wireless and cloud technologies

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Zinc oxide (ZnO) semiconductors can be used in a wide range of sensing applications, including environmental monitoring, biomedical testing (glucose, urea, DNA, PSA, etc.), optical sensing [29], as previously mentioned.

Fuel cell electric vehicles are increasing in popularity day by day. Fuel cells are relatively efficient devices, but the production of hydrogen has many losses with the current state of technology [30]. Water electrolysis can be done in many ways, one being proton exchange membrane (PEM) electrolysis [30]. Advantages of this system are low operating temperature, absence of non-wanted by-products, capability to produce limited amounts of hydrogen, saving on the production costs [30]. This method works in the opposite way compared to fuel cell energy production. Reaction environment is critical for the efficiency and effectiveness of the process [30]. In order to monitor and control the reaction thin film flexible integrated microsensor can be installed in PEM, providing real time measurements of: temperature, current, voltage and flow distribution [30]. Similar sensing technique can be applied to fuel cells, in the process of electricity production.

Oil changes are most common maintenance activities. If oil is not changed regularly many unwanted effects could be caused. When the oil moisture content is increased its permittivity changes, oil ageing can be accelerated, acidity increased and many undesired conditions can occur. These unwanted effects can be avoided by using an interdigitated impedance microsensor [31]. Micro sensor presented in this research could detect moisture content changes in the engine oil and alert the maintenance department to change the oil [31]. This can cut costs on the unwanted maintenance, breakdown line stoppage, delivery delays, or even costs of the oil. If the oil is used while it is good, and not changed preventively this can for sure make some savings.

For pneumatic devices, pressure control is one of the most important characteristics. For plastic bottles blowing, vacuum presses, sheet metal stamping, leak tests, dosing/filling operations pressure control is crucial factor. Novel design based on dual-gate graphene field-effect transistor with a vertically movable top-gate was analyzed by the team of researchers proving high potential for wide industrial application [32]. This type of sensor can be integrated into many processes as a mean of quality control, or in the product to enhance its longevity or features.

Many quality instructions or even standards require certain type and level of illumination for visual control areas. Widely used lighting solution is LED, but even though very efficient devices, LEDs dissipate some of the energy through heat [33]. This heat is then being conducted to the soldered joints and can cause malfunction, flickering, or even delamination of the joint [33]. An integrated microsensor for real-time measurement of temperature in the area of the soldered joint was presented and proved capable [33]. This sensor can detect changes in the temperature of the surface mounted LEDs and engage the control unit to act accordingly. When the temperature is higher, thermal resistance is higher so the efficiency of the unit decreases.

This microsensor can be used in many industrial equipment monitoring or maintenance systems. It could be also applied to many different types of products to improve product quality, energy efficiency and durability.
Micro and nano scale devices can also harvest energy [34]. Small devices based on the piezo-electric effect, capable of energy harvesting and sensing, are multifunctional, durable, and reliable [34], [35]. Triboelectric nanogenerators could provide energy harvesting, power themselves, sense and monitor environment changes, and interact with the environment [34], [35]. These self-powered devices are currently mostly used in medicine for drugs distribution, cell removal or bacteria and cancer cells killing. This technology is fairly new and a lot of advances are to be expected. There would be many industrial applications for micro and nano motors/robots in health and safety, maintenance, security and quality control. Applications in these areas are yet to be seen.

5. CONCLUSION

Research reviewed in this paper has shown that, although the industrial application of micro and nano technologies (MNTs) in the communication and monitoring processes is still relatively new, there is a great potential. Advances in technologies, Big Data, artificial intelligence (AI), Industrial Internet of Things (IIoT) create necessity for multifunctional, small, reliable, and inexpensive sensors. Combining MNT sensing, Big Data analytics and artificial intelligence can provide game changing systems for monitoring and controlling in terms of production, maintenance, health and safety, and quality control processes.
Fiber-optic sensors are widely used and commercialized components in areas like: large civil engineering structures, quantitative chemical processes, health and safety monitoring of composite materials and structural health monitoring. Optic systems are superior to metallic copper conductors when comparing: data transfer speed and quality, infrastructure longevity, attenuation level, electromagnetic wave interference and many more.
Optical fiber, micro, and nano-enabled sensors are highly capable of providing precise, real time, measurements and sensing of: different gasses, pH value, moisture content, humidity, shape changes, strain, acoustics, temperature, pressure, vibration characteristics, voltage, current, flow distribution, ions, and many more. Micro and nano enabled devices are also capable of energy harvesting from renewable sources, such as: wind, vibration, solar, light and sound. Micro and nano motors can harvest energy for the self-powering, but they can also interact with their environment and power up other components. Micro and nano motors have been proven capable to realise different advanced tasks such as: drug distribution in human body, bad cells removal, killing bacteria and cancer cells, and much more. Different focused research in high advanced areas like bioengineering also pointed out that similar concept can be successfully applied in traditional manufacturing industries as well.
The advantage of MNT-based sensors is that once they are developed they can be applied in almost every possible industrial sector, for wider purposes, like quality control. There are strong indications that future research should be focused on retrofitting older industrial equipment to Industry 4.0 by utilizing micro and nano sensors and components, for improved maintenance, quality control, production management, process parameters monitoring, and more through AI predictive systems that uses MNTs.

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REFERENCES

[1] A. Nayyar and A. Kumar, Eds., *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*. Cham: Springer International Publishing, 2020. doi: 10.1007/978-3-030-14544-6.

[2] A. Ustundag and E. Cevikcan, *Industry 4.0: Managing The Digital Transformation*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-57870-5.

[3] Z. Zakrzewski and B. Łaga, "Potential use of fiber-optic and Li-Fi systems in private 5G/6G networks dedicated to the industrial IoT," in *Optical Fibers and Their Applications 2020*, Bialowieza, Poland, Jun. 2020, p. 6. doi: 10.1117/12.2566060.

[4] D. G. Pascual, P. Daponte, and U. Kumar, *Handbook of Industry 4.0 and SMART Systems*. 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742: Taylor & Francis Group, LLC, 2020.

[5] D. L. Andersen, C. S. A. Ashbrook, and N. B. Karlborg, "Significance of big data analytics and the internet of things (IoT) aspects in industrial development, governance and sustainability," *Int. J. Intell. Netw.*, vol. 1, pp. 107–111, 2020, doi: 10.1016/j.ijin.2020.12.003.

[6] V. S. S. J. Kodidala, S. Akkala, S. K. Madupoju, V. S. S. T. Dasara, M. Juvvadi, and N. Thangadurai, "Big Data analysis of demand side management for Industrial IOT applications," *Mater. Today Proc.*, vol. 46, pp. 8313–8319, 2021, doi: 10.1016/j.matpr.2021.03.301.

[7] X. Zhang, X. Ming, and D. Yin, "Application of industrial big data for smart manufacturing in product service system based on system engineering using fuzzy DEMATEL," *J. Clean. Prod.*, vol. 265, p. 121863, Aug. 2020, doi: 10.1016/j.jclepro.2020.121863.

[8] C. Li, Y. Chen, and Y. Shang, "A review of industrial big data for decision making in intelligent manufacturing," *Eng. Sci. Technol. Int. J.*, vol. 29, p. 101021, May 2022, doi: 10.1016/j.jestch.2021.06.001.

[9] E. A. Gyasi, H. Handroos, and P. Kah, "Survey on artificial intelligence (AI) applied in welding: A future scenario of the influence of AI on technological, economic, educational and social

changes," *Procedia Manuf.*, vol. 38, pp. 702–714, 2019, doi: 10.1016/j.promfg.2020.01.095.
[10] M. Garouani, A. Ahmad, M. Bouneffa, and M. Hamlich, "AMLBID: An auto-explained Automated Machine Learning tool for Big Industrial Data," *SoftwareX*, vol. 17, p. 100919, Jan. 2022, doi: 10.1016/j.softx.2021.100919.
[11] F. Di Carlo, G. Mazzuto, M. Bevilacqua, and F. E. Ciarapica, "Retrofitting a Process Plant in an Industry 4.0 Perspective for Improving Safety and Maintenance Performance," *Sustainability*, vol. 13, no. 2, p. 646, Jan. 2021, doi: 10.3390/su13020646.
[12] S. S. V. Keshav Kolla, D. M. Lourenço, A. A. Kumar, and P. Plapper, "Retrofitting of legacy machines in the context of Industrial Internet of Things (IIoT)," *Procedia Comput. Sci.*, vol. 200, pp. 62–70, 2022, doi: 10.1016/j.procs.2022.01.205.
[13] Y. Pointurier, N. Benzaoui, W. Lautenschlaeger, and L. Dembeck, "End-to-End Time-Sensitive Optical Networking: Challenges and Solutions," *J. Light. Technol.*, vol. 37, no. 7, pp. 1732–1741, Apr. 2019, doi: 10.1109/JLT.2019.2893543.
[14] L. Gong *et al.*, "Optical orbital-angular-momentum-multiplexed data transmission under high scattering," *Light Sci. Appl.*, vol. 8, no. 1, p. 27, Dec. 2019, doi: 10.1038/s41377-019-0140-3.
[15] Y. Tu, Y. I. A. Al-Yasir, N. Ojaroudi Parchin, A. M. Abdulkhaleq, and R. A. Abd-Alhameed, "A Survey on Reconfigurable Microstrip Filter–Antenna Integration: Recent Developments and Challenges," *Electronics*, vol. 9, no. 8, p. 1249, Aug. 2020, doi: 10.3390/electronics9081249.
[16] B. Li, W. Piyawattanametha, and Z. Qiu, "Metalens-Based Miniaturized Optical Systems," *Micromachines*, vol. 10, no. 5, p. 310, May 2019, doi: 10.3390/mi10050310.
[17] Y. Xu, P. Lu, L. Chen, and X. Bao, "Recent Developments in Micro-Structured Fiber Optic Sensors," *Fibers*, vol. 5, no. 1, p. 3, Jan. 2017, doi: 10.3390/fib5010003.
[18] T. Grandal, S. Fraga, G. Castro, E. Vazquez, and A. Zornoza, "Laser Brazing metallic embedding technique for fiber optic sensors," Jeju, Korea, Republic of, Apr. 2017, p. 103236S. doi: 10.1117/12.2263974.
[19] P. Fan, S. Goel, X. Luo, Y. Yan, Y. Geng, and Y. Wang, "An atomistic investigation on the wear of diamond during atomic force microscope tip-based nanomachining of gallium arsenide," *Comput. Mater. Sci.*, vol. 187, p. 110115, Feb. 2021, doi: 10.1016/j.commatsci.2020.110115.
[20] Y. Wang, Z. Liang, W. Zhao, X. Wang, and H. Wang, "Effect of ultrasonic elliptical vibration assistance on the surface layer defect of M-plane sapphire in microcutting," *Mater. Des.*, vol. 192, p. 108755, Jul. 2020, doi: 10.1016/j.matdes.2020.108755.
[21] Y. Liu, A. Zhou, and L. Yuan, "Multifunctional fiber-optic sensor, based on helix structure and fiber Bragg gratings, for shape sensing," *Opt. Laser Technol.*, vol. 143, p. 107327, Nov. 2021, doi: 10.1016/j.optlastec.2021.107327.
[22] Y. Sun, J. Liu, Z. Xue, Q. Li, C. Fan, and X. Zhang, "A critical review of distributed fiber optic sensing for real-time monitoring geologic CO2 sequestration," *J. Nat. Gas Sci. Eng.*, vol. 88, p. 103751, Apr. 2021, doi: 10.1016/j.jngse.2020.103751.
[23] S. Weber *et al.*, "Application of fibre optic sensing systems to measure rotor blade structural dynamics," *Mech. Syst. Signal Process.*, vol. 158, p. 107758, Sep. 2021, doi: 10.1016/j.ymssp.2021.107758.
[24] S. R. H. Largani, H.-Y. Wen, Y.-C. Liu, and C.-C. Chiang, "Humidity and temperature sensing by monitoring changeable length and diameter of bent fiber optics attached to Faraday mirror reflector," *Opt. Fiber Technol.*, vol. 65, p. 102633, Sep. 2021, doi: 10.1016/j.yofte.2021.102633.
[25] Y. Yu, T. Vincent, J. Sansom, D. Greenwood, and J. Marco, "Distributed internal thermal monitoring of lithium ion batteries with fibre sensors," *J. Energy Storage*, vol. 50, p. 104291, Jun. 2022, doi: 10.1016/j.est.2022.104291.
[26] C.-Y. Lee *et al.*, "Integrated microsensor for real-time microscopic monitoring of local temperature, voltage and current inside lithium ion battery," *Sens. Actuators Phys.*, vol. 253, pp. 59–68, Jan. 2017, doi: 10.1016/j.sna.2016.10.011.
[27] S. Thakkar, L. F. Dumée, M. Gupta, B. R. Singh, and W. Yang, "Nano–Enabled sensors for detection of arsenic in water," *Water Res.*, vol. 188, p. 116538, Jan. 2021, doi: 10.1016/j.watres.2020.116538.
[28] J. Francis and P. A. Michael, "Investigation of micro/nano motors based on renewable energy sources," *Mater. Today Proc.*, vol. 27, pp. 150–157, 2020, doi: 10.1016/j.matpr.2019.09.138.
[29] R. Sha, A. Basak, P. C. Maity, and S. Badhulika, "ZnO nano-structured based devices for chemical and optical sensing applications," *Sens. Actuators Rep.*, p. 100098, Apr. 2022, doi: 10.1016/j.snr.2022.100098.
[30] C.-Y. Lee, C.-H. Chen, S.-C. Li, and Y.-S. Wang, "Development and application of flexible integrated microsensor as real-time monitoring tool in proton exchange membrane water electrolyzer," *Renew. Energy*, vol. 143, pp. 906–914, Dec. 2019, doi: 10.1016/j.renene.2019.05.071.
[31] H. Liu, X. Tang, H. Lu, W. Xie, Y. Hu, and Q. Xue, "An interdigitated impedance microsensor for detection of moisture content in engine oil," *Nanotechnol. Precis. Eng.*, vol. 3, no. 2, pp. 75–80, Jun. 2020, doi: 10.1016/j.npe.2020.04.001.
[32] K. Tamersit, M. Kotti, and M. Fakhfakh, "A new pressure microsensor based on dual-gate graphene field-effect transistor with a vertically movable top-gate: Proposal, analysis, and optimization," *AEU - Int. J. Electron. Commun.*, vol. 124, p. 153346, Sep. 2020, doi: 10.1016/j.aeue.2020.153346.
[33] H. Choi, W. Choi, J. Lim, and J. Choi, "Integrated microsensor for precise, real-time measurement of junction temperature of surface-mounted light-emitting diode," *Sens. Actuators Phys.*, vol. 298, p.

111578, Oct. 2019, doi: 10.1016/j.sna.2019.111578.

[34] Q. Shi, T. He, and C. Lee, “More than energy harvesting – Combining triboelectric nanogenerator and flexible electronics technology for enabling novel micro-/nano-systems,” *Nano Energy*, vol. 57, pp. 851–871, Mar. 2019, doi: 10.1016/j.nanoen.2019.01.002.

[35] R. A. Surmenev, R. V. Chernozem, I. O. Pariy, and M. A. Surmeneva, “A review on piezo- and pyroelectric responses of flexible nano- and micropatterned polymer surfaces for biomedical sensing and energy harvesting applications,” *Nano Energy*, vol. 79, p. 105442, Jan. 2021, doi: 10.1016/j.nanoen.2020.105442.

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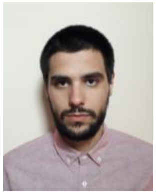

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EDUCATIONAL KNOWLEDGE GAPS IN THE CONTEXT OF INDUSTRY 4.0: ACADEMICS' AND COMPANIES' PERSPECTIVE

Zoran ANIŠIĆ
Nenad MEDIĆ

Abstract: *Recent developments in the industry has resulted in the new requirements for the needed knowledge of employees. Companies, as well as higher education institutions, are becoming aware of the necessity to prepare employees to adapt to the working principles of new industrial paradigm called Industry 4.0. The aim of this paper is to present the results of the conducted research on the sample of 54 Serbian companies and 34 academics from the University of Novi Sad, Faculty of Technical Sciences, Department of Industrial Engineering and Management that indicate the knowledge gap for specific knowledge from the perspective of Industry 4.0. The results of the research indicate that there is a greater demand than the current offer for specific knowledge related to the implementation of the Industry 4.0 concept. These results could serve as an input for the development of study programs which will be more oriented towards the Industry 4.0 knowledge and competencies.*

Keywords: *Industry 4.0; education; study programs; knowledge gap*

1. INTRODUCTION

Companies need a new strategic approach in human resource management, in order to adequately deal with the challenges posed by the implementation of digital technologies and the concept of Industry 4.0 in the business environment. As the complexity of the processes increase, there is a need for a growing number of employees with higher education and specific knowledge and skills [1]. One of the key necessities in order to realize the transition to modern trends in production and service systems in the best possible way is to provide as much as possible skilled workforce [2]. The new situation on the market has led the academic community to be interested and get actively involved in creating solutions that include improvement of current study programs to produce new generation of workforce which in turn could easily respond to different market needs resulting from the introduction of Industry 4.0 [3].
This topic is extremely important in the field of industrial engineering and management, which is a combination of social and engineering competencies, given that within Industry 4.0 knowledge in both fields are required [4]. For this reason, it is necessary to investigate what competencies employees need in the context of Industry 4.0, as well as the current representation of these competencies in trainings organized by companies and study programs in higher education institutions where programs related to industrial engineering and management are present [5].

This paper will present the results of the research that indicate the current offer and expected demand for specific knowledge from the perspective of Industry 4.0, in the study programs of master's academic studies in Industrial Engineering and Engineering Management from the perspective of the academics that are working in this field and employees form manufacturing and service companies. Moreover, the results obtained from these two groups will be compared and analysed.
The rest of the paper is organized in the following way. The next section describes data gathering procedure as well as the structure of the instruments used, coupled with same basic sample descriptions. Methods that are used for the purpose of this paper are briefly mentioned as well. This is followed by the results and discussion section which constitutes the main and most important part of the paper. The last section is reserved for conclusions of the paper, with stated limitations of the study and consequently propositions for further research avenues.

2. METHODS AND DATA

For the purpose of this research the data was gathered through the quantitative survey. More specifically, the questionaries were designed and distributed among stakeholder groups (i.e., companies and academics). The main parts of the questionnaire that will be in the focus of the analysis in this paper are related to the following topics for both companies and academics:

- Knowledge, skills and competencies
    - Problem Solving and Decision Making

- Team Working
- Strategic Management
- Entrepreneurial Mindset and Skills
- Investment and Finance
- Industrial Organization
- Industrial Marketing
- Communication Skills
- Logistics
- Innovation and Change Management
- Leadership Issues
- Project Management
- Operations Management
- Quality Management
- Ergonomics
- Safety of Work

- Operational tools
  - Computer-based Statistic Competencies
  - Management Software Tools (e.g., ERP, CRP, etc.)
  - Cyber Security Competencies
  - Big Data Analysis
  - IoT Monitoring Competencies
  - Sensor-based Monitoring Competencies
  - Machine Learning/AI Competencies
  - Augmented/VR Competencies
  - 3D Printing Competencies

Furthermore, two additional topics were covered only for academics:

- Knowledge transfer methodology
  - Traditional Face-to-Face Lectures
  - Seminars/Tutorials
  - Workshop
  - Field Trips (factories/companies)
  - Web-based: Synchronous Learning on the Web
  - Web-based: Asynchronous Learning on the Web
- Learning activities
  - Theoretical Studies (books, educational materials, …)
  - Seminars/Exercises
  - Case-based Learning
  - Individual Projects
  - Group Projects
  - University Physical Labs
  - University Virtual/Computer Labs
  - Experiential Learning

In order to make as easy as possible the distribution and completion of the questionnaires, they were coded in MS Forms. This allowed us to automatically collect answers and to monitor the number of answers received on a daily basis, so as to implement corrective actions in order to reach a significant number of answers. During the collection period (01/11/2021-15/12/2021), an invitation to complete the questionnaires was sent to the stakeholders, providing them with a brief overview of the research aims together with the link to the corresponding questionnaire.

At the end of the collection period, we have acquired 87 properly completed questionnaires, 54 from companies and 33 from academics. Each question presented in the questionnaire reflected a certain competency for which it was required from the respondent to assess the frequency of adoption (i.e., offer) and the frequency of the expected adoption (i.e., demand). For both offer and demand, the respondent could select one out of five possible choices: not offered/required, low, medium, high, and don't know. The complete answers are then used to evaluate the gap between offer and demand. In order to enable quantitative analysis, a numerical value was linked to each of the possible answers as shown in Table 1.

Table 1. Numerical values adopted for each answer in the analysis of questionnaires' results

Answer	Value
"not offered/required"	0
"low"	1
"medium"	2
"high"	3
"don't know"	null

All analysis presented in this paper are based on the statistics. More precisely, for the purpose of this paper we used descriptive statistics and comparative analysis. This includes clustering of the data obtained by each stakeholder, as well as comparative analysis of the data obtained from different stakeholders (i.e., companies and academics).

In order to better understand the structure of the sample, some basic descriptive statistics will be presented in the following figures. Figures 1 and 2 present some general information (i.e., company size and production processes) about the companies that participated in the research.

From Figure 1 we can see that companies of all sizes are represented in the sample. Furthermore, companies that are oriented to services are equally represented in the sample as the ones that are oriented towards both manufacturing by parts or process manufacturing, as it is shown in Figure 2.

As far as academics that participated in the research, all of them are professors in the field of industrial engineering and management. Figures 3 and 4 provide same insight about the study programs and size of the universities at which these professors are employed. Mainly, the professors are working in the study programs related to industrial engineering or engineering management, but other study programs in the field are represented in the sample in minor percentage of cases as it is presented in Figure 3. Finally, from Figure 4 we can see that professors who participated in the research are employed at universities with various number of students enrolled.

3. RESULTS AND DISCUSSION

Results will be presented from the perspective of companies and academics. Furthermore, the comparison between these two groups will be carried out on some important issues.

3.1. The companies' perspective

An overview of the results obtained from the analysis of answers gathered from companies are presented in Figure 5. These results are showing the offer, the demand, and the gap for each of the observed competencies.

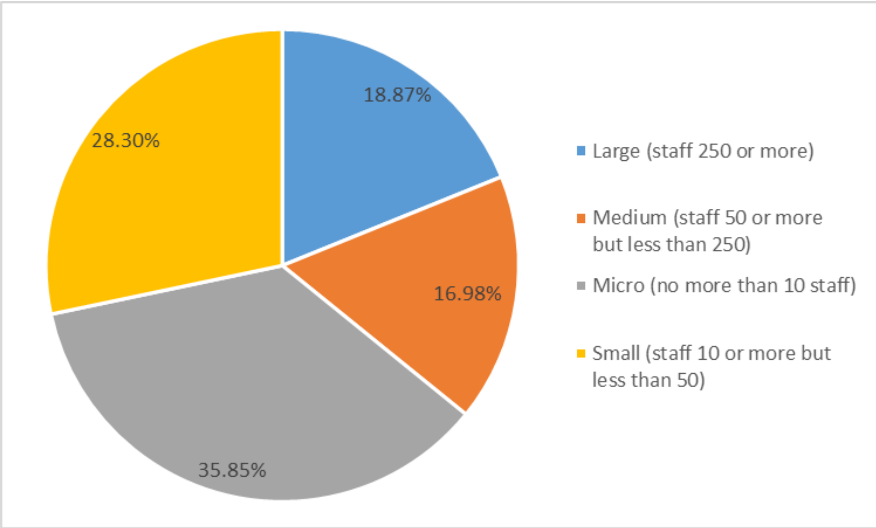

Fig. 1. Size of the companies which completed the questionnaire

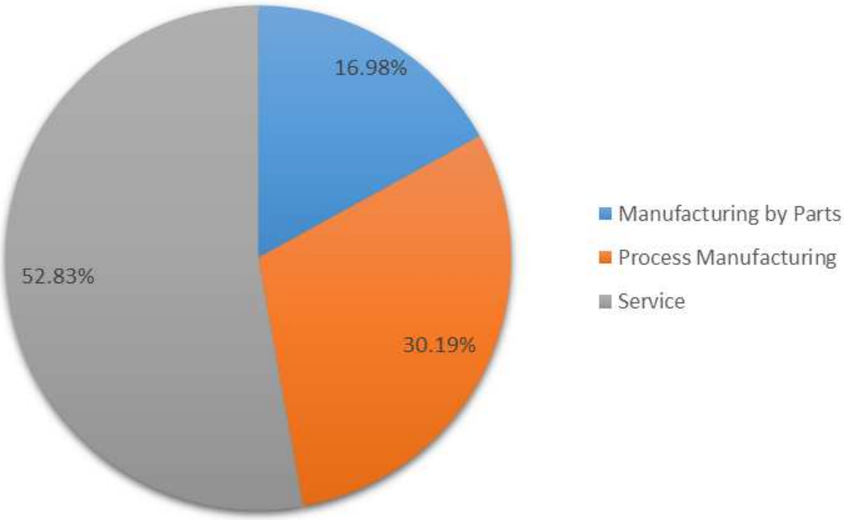

Fig. 2. Production processes of the companies which completed the questionnaire

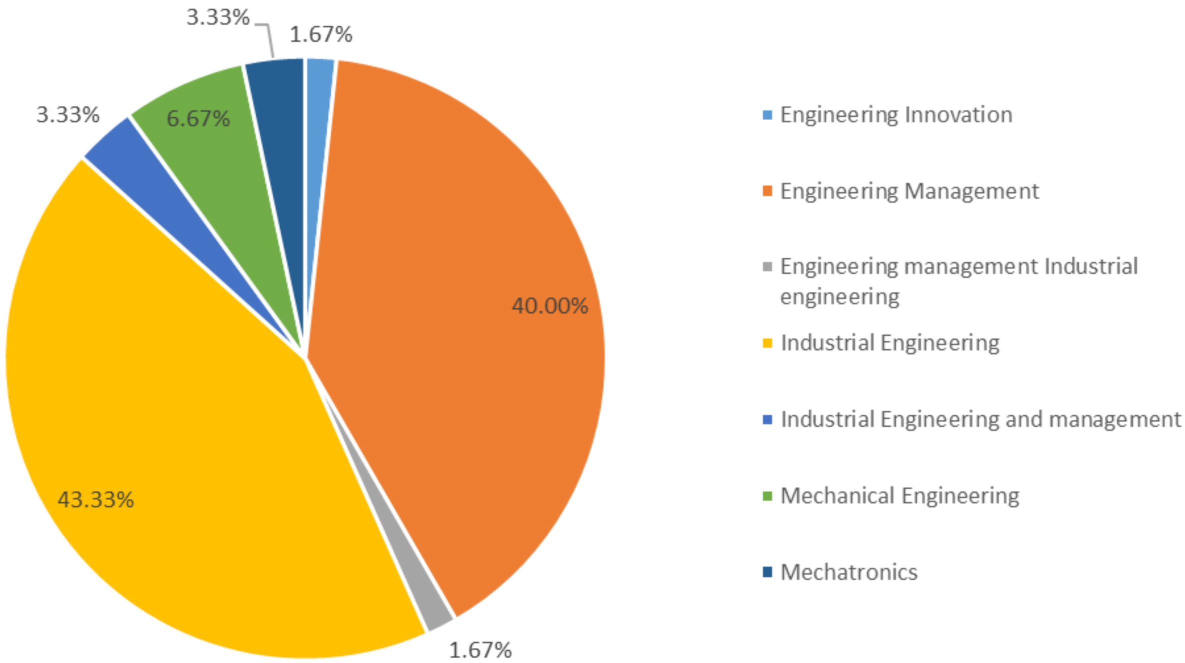

Fig. 3. Study programs of the universities at which participating professors are employed

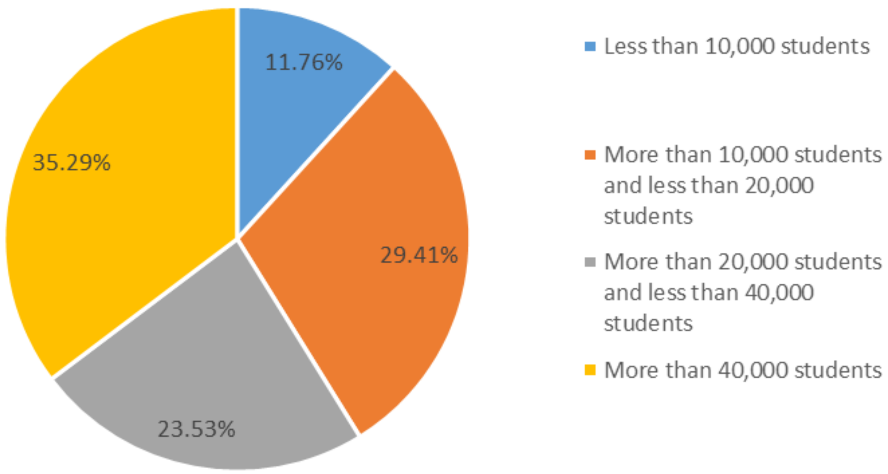

Fig. 4. Size of the universities at which participating professors are employed

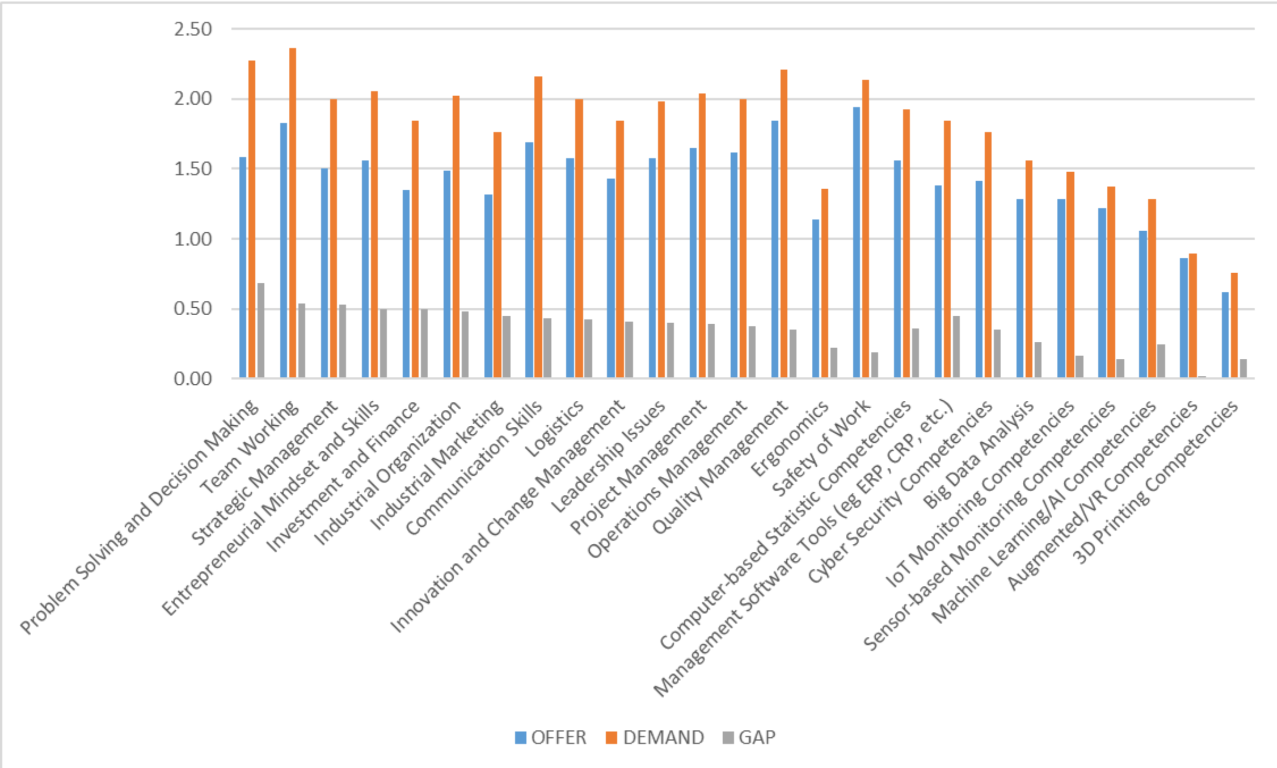

Fig. 5. Offer, demand, and gap for each of the observed competencies from the companies' perspective

Overall analysis shows that there is a net positive gap for each of the competencies observed, which means that there is a higher demand than the offer in all cases. If we analyse the knowledge, skills and competencies, we can see that the highest gap is present for Problem solving and decision making, Team working, and Strategic management. The lowest gap is linked with Ergonomics and Safety of work. Furthermore, considering operational tools the highest difference is noticed for Management software tools, Computer-based statistic competencies, and Cyber security competencies. The lowest gap is linked with Augmented/VR competencies.

One interesting point of view is looking at the differences in answers received, between service companies and manufacturing companies, which are characterized by different production processes. For the purpose of these analyses, answers received were clustered by companies' sectors. Two clusters have been considered, as detailed in Table 2.

Table 2. Clustering of companies which responded to questionnaire

Cluster	Production process	#
Manufacturing	Manufacturing by Parts Process Manufacturing	25
Service	Service	29

Figure 6 presents the differences between service and manufacturing companies considering the average demand for each of the competencies.

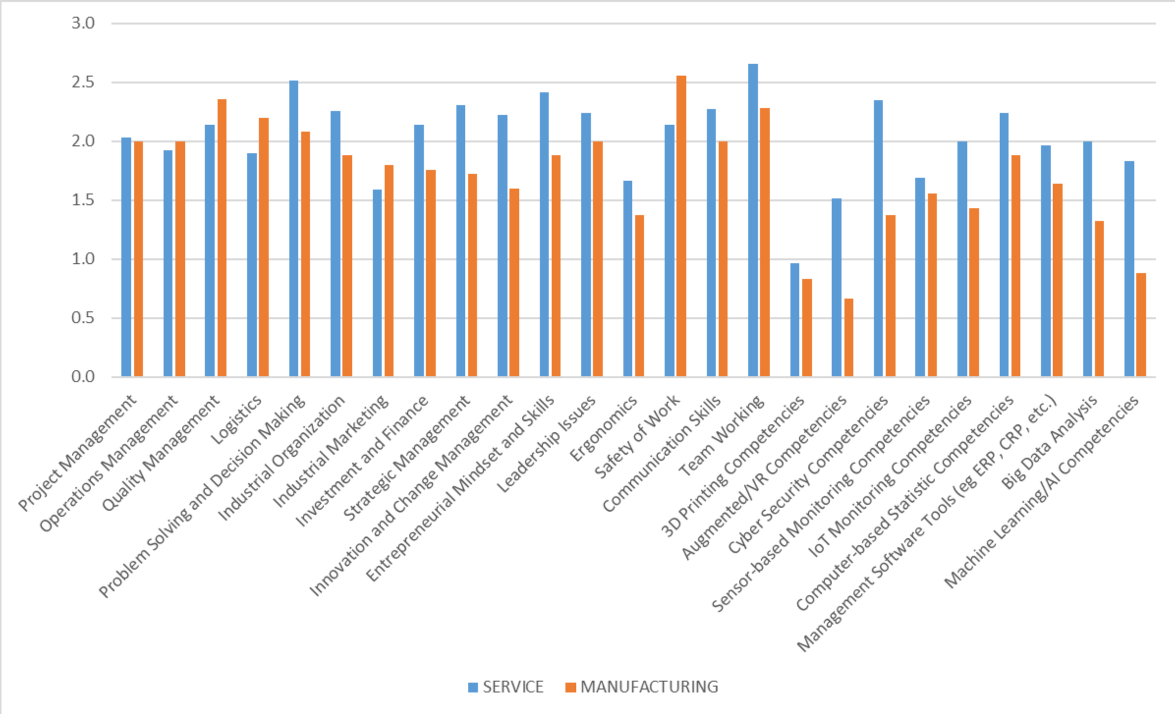

Fig. 6. Results of the analysis of answers clustered in service and manufacturing groups

Observing the results presented in Figure 6, it is obvious that competencies required by companies are affected by their production process type. Looking at manufacturing cluster, knowledge, skills and competencies with high demand values are Quality management, Safety of work, Team working, Logistics, and Problem solving and decision making. Interestingly, the service cluster also showed high demand in Team working and Problem solving and decision making. Furthermore, companies belonging to the Service cluster showed high demand for Entrepreneurial mindset and skills and Leadership issues. By analysing the answers on operational tools grouped in service and manufacturing clusters, significant differences were observed. The most obvious difference is higher demand in the service cluster compared to the manufacturing cluster for each of the competencies. The highest difference is noticed in competencies such as Cyber security and Machine learning/Artificial intelligence.

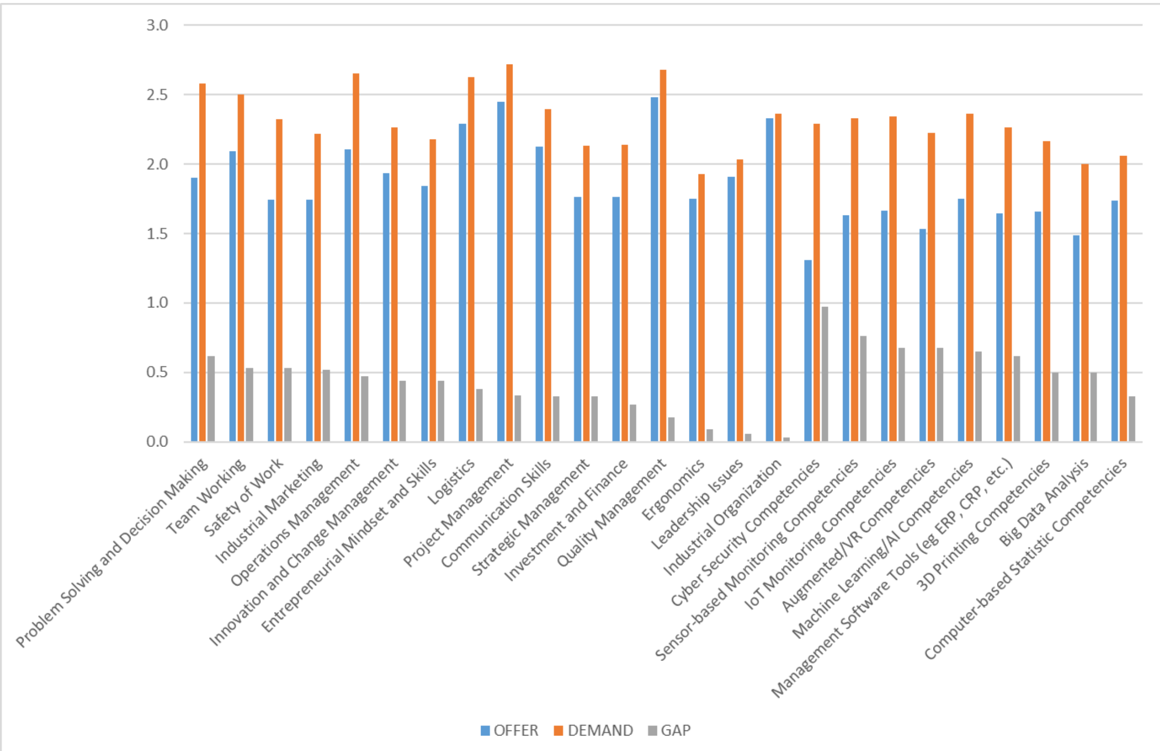

Fig. 7. Offer, demand, and gap for each of the observed competencies from the academics' perspective

3.2. The academics' perspective

An overview of the results obtained from the analysis of answers gathered from academics are presented in Figure 7. These results are showing the offer, the demand, and the gap for each of the observed competencies. Concerning knowledge, skills and competencies, the following competencies with high demand are identified: Project management, Quality management, Operations management, Logistics, Problem solving and decision making, and Team working. Furthermore, the highest gap is noted in Problem solving and decision making and Team working. Safety at work and Industrial marketing also have high gap between demand and offer, but with lower values of demand compared to the previously mentioned competencies. The lowest demand followed by the lowest gap is present in competencies such as Leadership issues and ergonomics.

Analysing the operational tools investigated, a high demand is noticed in both analytical competencies (i.e., Machine learning/Artificial intelligence competencies and Management software tools) and digital competencies (i.e., IoT monitoring, Sensor-based monitoring, and Cyber security). Highest gap score values are present in digital competencies such as Cyber security and Sensor-based monitoring. For all the operational tools investigated, a net positive gap is obtained, meaning that there is a higher demand than the current offer in all cases.

Figure 8 is oriented towards the results focused on Knowledge transfer methodologies and Learning activities.

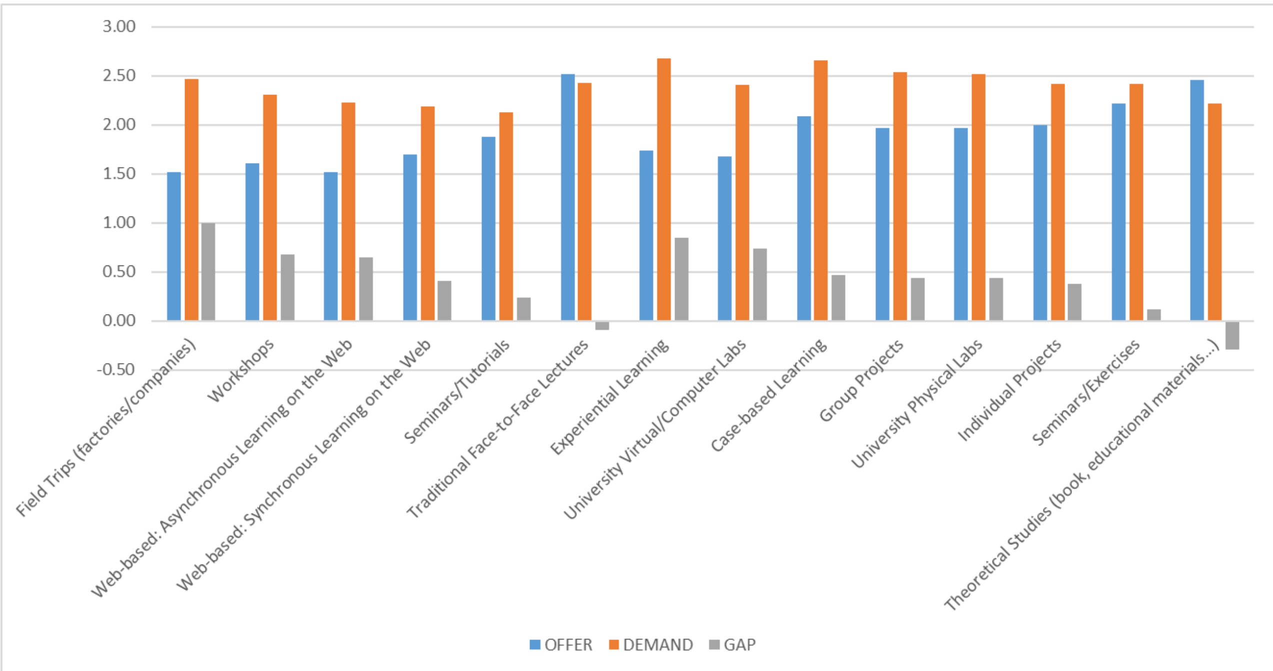

Fig. 8. Offer, demand, and gap values for knowledge transfer methodologies and learning activities expressed by academics

Considering knowledge transfer methodologies, for most of the methodologies investigated a positive gap is obtained. Only in case of the Traditional face-to-face lectures, the demand score is lower than the offer. The highest gap score value is obtained for Field trips which shows that academics are aware of the importance of improving the interaction of students with the industrial environment. Among web-based knowledge transfer methodologies, asynchronous modality is preferred to synchronous one.

In case of learning activities, academics expressed the highest demand for Experiential learning and Case-based learning; they are followed by Group projects, University physical labs, and Seminar/Exercises. The highest gap values are observed in the case of Experiential learning and University virtual/computer labs. Only in the case of traditional Theoretical studies, demand score value is lower than the offer value, thus indicating negative gap value.

In this part of the questionnaire, two further questions were asked to academics. They were both intended to investigate the role of industry in study programs. Results of the answers' analysis are presented in Figures 9 and 10. Figure 9 shows that in the majority of the study programs there is an internship offered. Length of this internship varies, and in more than half of the cases is between 1-4 weeks. Nevertheless, the internal demand expressed by academics stresses out the need to increase the presence of longer internships (4-8 weeks) in study programs.

As far as the presence of industry professors in study program courses, in less than 15% of cases industry professors hold 4 or more courses, while in 35% of cases they are not present at all. More than half of the academics interviewed expressed the need for the presence of industry professors in study programs in at least 2 courses as presented in Figure 10.

Fig. 9. Results of the academics' survey on internship length in study programs

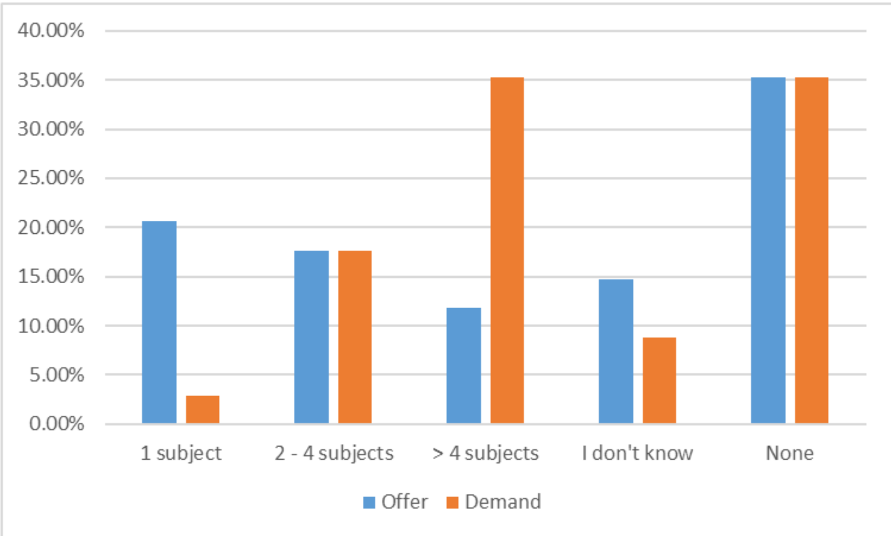

Fig. 10. Results of the academics' survey on the presence of courses held by industry professors in study programs

By comparing the knowledge demand expressed by companies and the offer expressed by academics in the area of knowledge, skills and competencies, it is possible to identify one major inconsistency. It concerns the competencies characterized by a high value of both companies' demand and gap. The gap here is evaluated as the difference between companies' demand and HEIs' offer. Among these competencies, the highest gap between what is required by companies and what is offered by HEIs is noticed in Team working, Problem solving and decision making, and Safety of work. These are the competencies that should definitely be more present in HEIs offer in order to meet companies' requirements.
With reference to operational tools investigated, again similar inconsistency is observed. Computer-based statistical competencies, Management software tools, Cyber security competencies, and Big data analysis in which a gap is observed between companies' demand and HEIs' offer. Therefore, the focus of HEIs' offer should be on increasing the offer of these competencies in study programs.
Finally, the knowledge demand expressed by companies has been compared with the demand expressed by academics working in HEIs. The results are presented in Figure 12.
Knowledge demand expressed by HEIs is based on the knowledge of academics of the job market. It is interesting noting how demand expressed by academics is higher than the demand expressed by companies for each competency, thus denoting a good knowledge of academics of companies' knowledge needs. This is confirmed also by the low values observed in the differences between HEI's demand and companies' demand. The high values of gap between HEI's demand and companies' demand are noted for the following competencies: Project management, Logistics, Operations management, and Ergonomics. The same line of reasoning applies to operational tools. The high values of gap between HEI's demand and companies' demand are noted for practically all of the competencies observed.

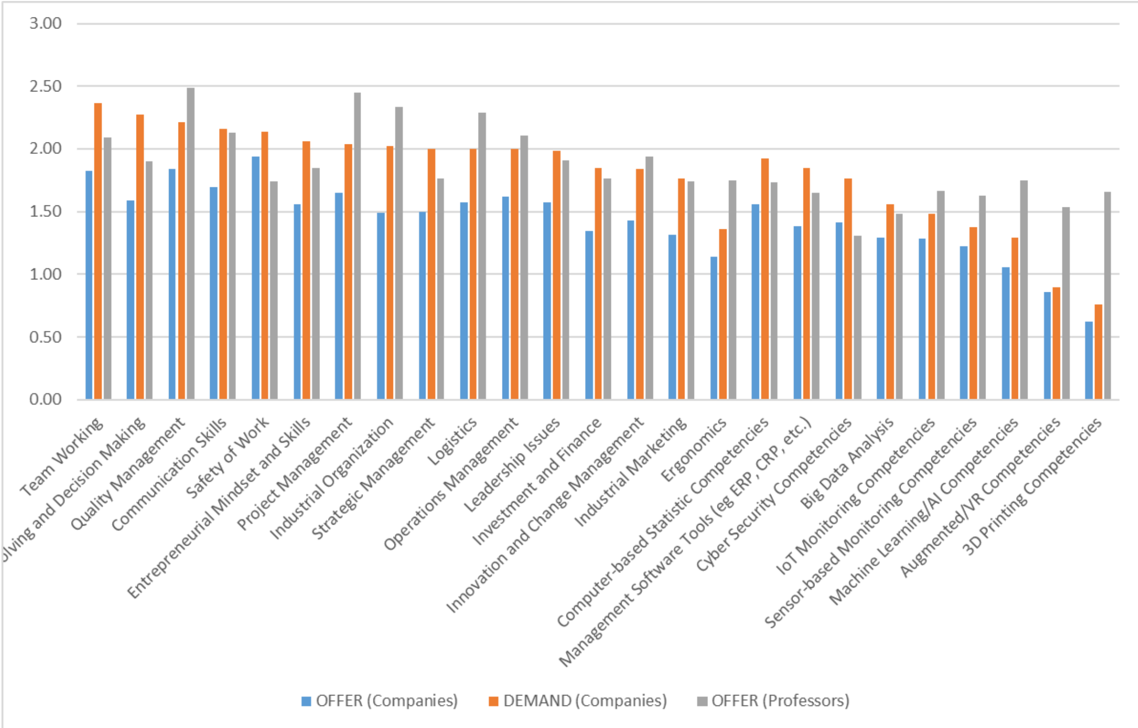

Fig. 11. Offer and demand expressed by companies compared with offer expressed by academics

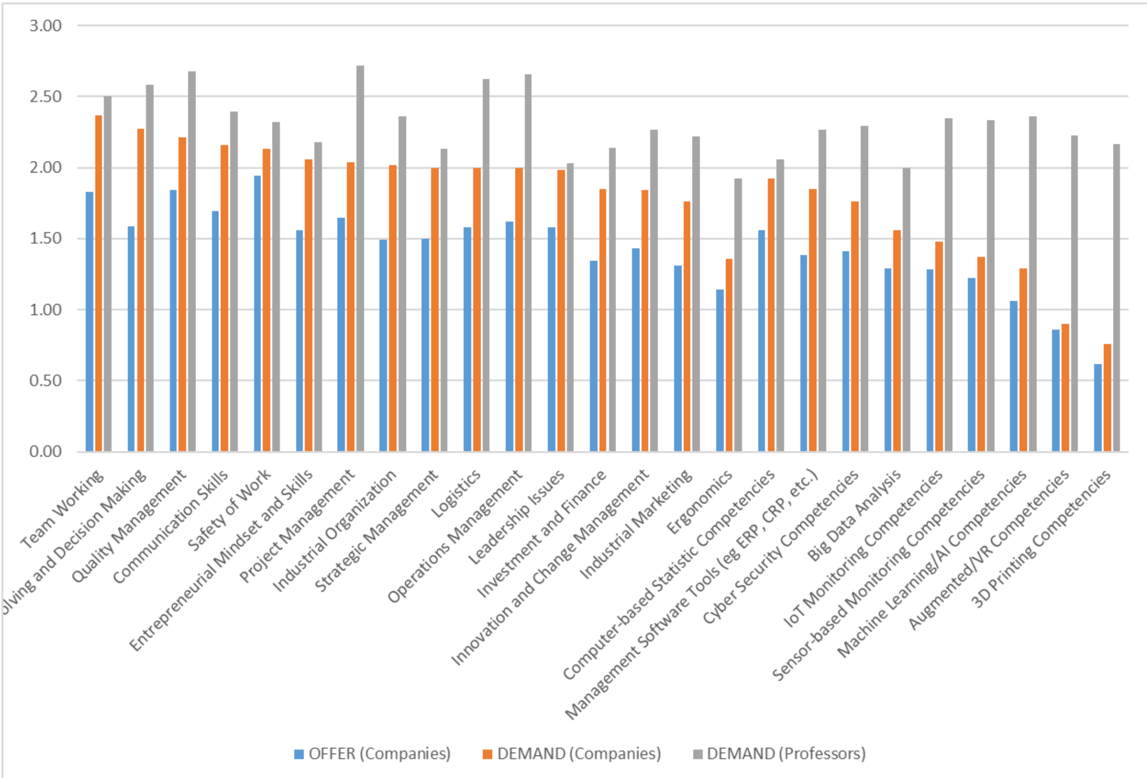

Fig. 12. Offer and demand expressed by companies compared with demand expressed by academics

4. CONCLUSION

This paper presents the results of a study in which two different groups of respondents (i.e., companies and professors) participated in order to determine the current offer and expected demand for specific knowledge from the perspective of Industry 4.0, in the study programs in the field of industrial engineering and management, as well as the opinion of employees in manufacturing and service companies on these issues. For these purposes, data were collected using questionnaires, and the results were presented using descriptive statistics.

The results of the research show that all respondents are aware of the upcoming trend in production and service systems based on digitalization and that in this sense, adjustments and improvements are necessary.

Improvement of the existing study programs in the field of industrial engineering and management based on the information obtained from companies is one of the possible ways to respond to rapid and frequent changes in market demands.
This research is based on the data collected in the Republic of Serbia, and for that reason is limited to this region. Further research could include companies and higher education institutions from other regions, especially those considered more developed in industrial terms. In this way, a comparative analysis could be made between the results collected in developing countries and those that are more deeply involved in this transformation process.

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REFERENCES

[1] Hecklau, F., Galeitzke, M., Flachs, S., Kohl, H.: Holistic Approach for Human Resource Management in Industry 4.0. *Procedia CIRP*, vol. 54, pp. 1–6, 2212-8271, 2016.
[2] Benešová, A., Tupa, J.: Requirements for Education and Qualification of People in Industry 4.0. *Procedia Manufacturing*, vol. 11, pp. 2195–2202, 2351-9789, 2017.
[3] Richert, A., Shehadeh, M., Plumanns, L., Gros, K., Schuster, K., Jeschke, S.: Educating engineers for industry 4.0: Virtual worlds and human-robot-teams. *IEEE Global Engineering Education Conference (EDUCON),* Abu Dhabi, United Arab Emirates, 10-13 April 2016, pp. 142-149, 978-1-4673-8633-3.
[4] Popkova, E., Zmiyak, K.: Priorities of training of digital personnel for industry 4.0: social competencies vs technical competencies. *On the Horizon*, vol. 27, no. 3/4, pp. 138–144, 1074-8121, 2019.
[5] Ivanov, D., Tang, C. S., Dolgui, A., Battini, D., Das, A.: Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management," *International Journal of Production Research.*, vol. 59, no. 7, pp. 2055–2078, 0020-7543, 2021.

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EDUCATION OF PRODUCTION ENGINEERS FOR INDUSTRY 4.0

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Abstract: *Universities and faculties are some of the key players in ensuring the dissemination of knowledge and the development of skills related to Industry 4.0. This industry will increasingly require professionals to perform complex and indirect tasks in many areas, including production engineering. The emergence of Industry 4.0 is leading to a change in the way production engineers are educated at university. The aim of this paper is to provide an overview of possible ways to improve the education of production engineers in the regions of Vojvodina and Republic of Srpska in light of the requirements of Industry 4.0.*

Keywords: : *Industry 4.0, production engineering, education*

1. INTRODUCTION

The term Industry 4.0 stands for the fourth industrial revolution, which is defined as a new level of organization and control across the entire value chain of the product lifecycle, and is focused on increasingly individualized customer requirements. I4.0 refers to the integration of people into production in order to continuously improve the production process while reducing costs and production time. It is clear that training as we know it today will have to change its character significantly. In line with new technologies, changes in modern education, especially higher education, are needed to effectively train employees to meet the challenges of the new era of industrialization.
Education 4.0 is a new education system focused on the application of digital technologies through personalized education and intelligent connection of machines, electronics and software. Therefore, in these integrated engineering fields, it is necessary to define new ways of working and thinking, which includes the application of new approaches in education. Technologies associated with the "Revolution 4.0" include Big Data (Data Analytics), Internet of Things (IoT), Cyber-Physical Systems (CPS) Artificial Intelligence, Cloud Computing, Machine Learning, Virtual Reality, Augmented Reality, etc. These technologies are the fundamental paradigms of I4.0 and represent the pillars for the transformation from a traditional enterprise to a digital enterprise.
The rapid changes resulting from the development of communication technologies cannot be clearly predicted, and therefore the questions of how and what to train become fundamental issues. For this reason, the research content of this paper aims to analyse and identify areas in which the university education of production engineers should be directed in the future according to the requirements of I4.0.

2. UNIVERSITY 4.0 - EDUCATION OF PRODUCTION ENGINEERS

Industry 4.0 is a term for the further development of production and value creation systems that connect the real and digital worlds. It is widely understood as a new phase of the industrial revolution that, after mechanization, electrification and computerization of industry, is now leading to Cyber-Physical Systems - CPS - with the Internet of Things, smarter networking of machines around the world, storage and resource systems, making extensive use of the industrial Internet and alternative connections that enable networking of dispersed devices. CPSs are combined with a whole range of other achievements, such as 3D printing, adaptive robotics, machine-to-machine (M2M), cloud computing, business model innovation, smart factory, mobile devices, etc. I4.0 aims to develop a completely new concept of production automation.
The question is no longer "Is Industry 4.0 coming?", but "How fast is it coming?". Ten years ago, the term "Industry 4.0" might have seemed fashionable, like 3D printing and generative product design. Today, we can say with certainty that Industry 4.0 is becoming our near

reality, and we urgently need to adapt to it. It is clear that the concept of Industry 4.0 will affect all entities, both the economy and other segments of society (e.g., education), but it is not clear what steps we can and must take. The transition to Industry 4.0 is not limited to specific production sectors or to specific companies.

There is currently a shortage of professionals capable of taking on Industry 4.0 tasks, and unfortunately many schools and universities are still educating students who are not up to the demands of this I4.0 concept. Today's universities were founded from the perspective of three previous industrial revolutions that do not offer competencies for Industry 4.0. For this reason, universities and higher education systems must be adapted to educate and prepare students for the industry of the future. Traditional teaching methods have limited effectiveness in developing students' competencies for future manufacturing environments. Production as a subject cannot be effectively treated in the classroom alone. New learning approaches are needed that: provide training in real production environments, modernize the learning process and bring it closer to industrial practice, leverage industrial practice by adopting new production skills and technologies, etc.

Figure 1 shows the different industrial and academic revolutions and the analogy of their common characteristics. The first university revolution (University 1.0) is characterised by learning limited to a small number of privileged students. The second university revolution (University 2.0) is characterised by the massification of education and the democratisation of access to knowledge. The third university revolution (University 3.0) represents an era of integration of digital devices as a means of teaching and learning. The concept of the fourth university revolution (University 4.0) must answer the following questions: "How can students be prepared to succeed in the global information economy?", "What skills should students acquire before they graduate?", "What is the best way to acquire these skills?" In Germany, for example, more than 80 occupations have been modified or created since 2010 to meet industry demands for necessary business and social change (source: http://www.bibb.de/).

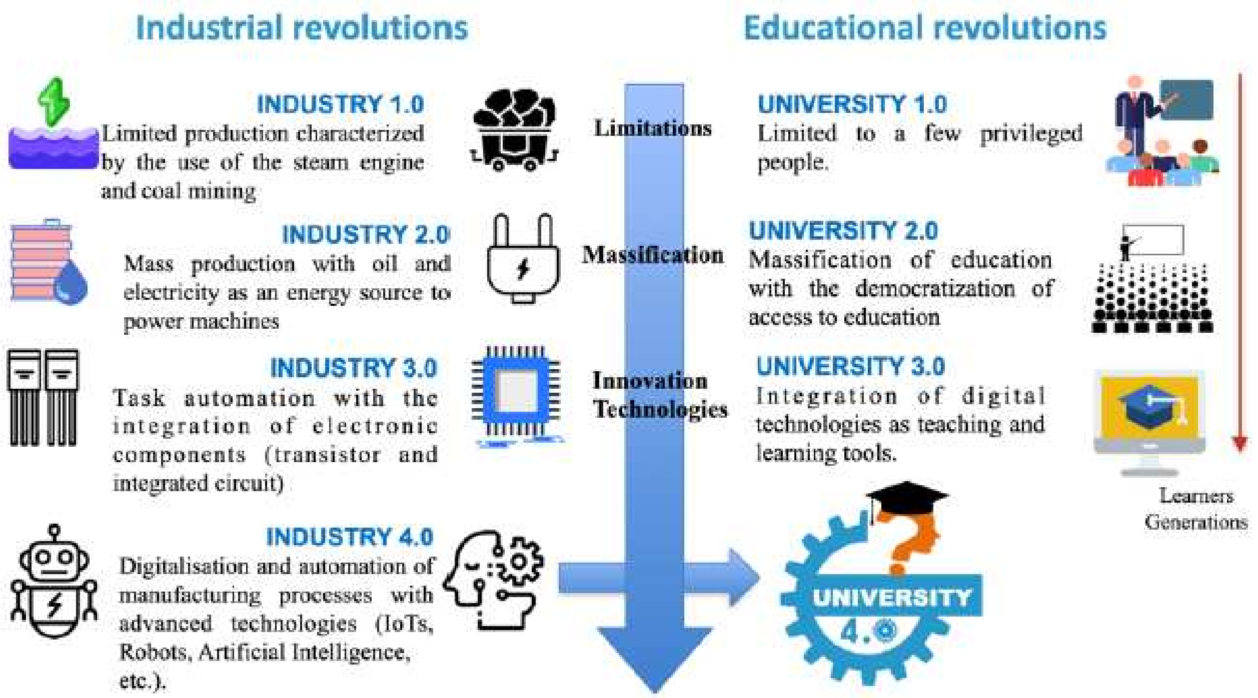

Fig.1 Analogy between the different industrial and university revolutions [1]

Qualification through education or training does not necessarily mean that a person is competent. Competence means successfully demonstrating the competencies required to qualify I4.0 topics. In the context of future trends in education and training for Industry 4.0, qualifications should be distinguished from competencies. Qualifications for Industry 4.0 are objectively describable, teachable and learnable knowledge and skills that are functional, while the concept of competencies for Industry 4.0 encompasses individual aspects of personality that are geared toward (professional) usefulness. In this respect, the main goal of competence development is the formation of personality structures for coping with the requirements of change in Industry 4.0 as part of the transformation process and the further development of economic and social life. The new technologies of intelligent production or advanced production involve fundamental changes in the division of labor between humans and machines. This will have a significant impact on the tasks, quality of work and skills of workers. Workers will be confronted with changed work processes and business models as well as new technologies. The transformation of the work environment will change job profiles and thus demand a broad range of competencies from employees. Experts and production specialists will have to answer many technical questions and organizational problems.

To turn our engineers into "Engineers 4.0" ready for the next round of innovation, universities and faculties must research, adapt, and modernize their programs of study.

What knowledge and technologies will be needed to put the I4.0 concept into practice in manufacturing is critical. The moment we research (identify) and recognize areas of new knowledge, we as faculties must begin to adapt quickly. In order for our manufacturing engineers to be at the "top of the game" called Industry 4.0, we as faculties must adopt new paradigms early or risk the future taking place on the margins of education.

2.1. Competencies and skills for Industry 4.0

To ensure the successful transition of traditional Serbian industry to Industry 4.0, highly qualified engineers and employees are needed. It is clear that engineering education needs to change and be redesigned. An estimated 35% of skills and competencies have changed [2], and traditional formal education does not meet the requirements to provide a workforce for the demands of the Industry 4.0 concept. Analytical thinking and innovation, active learning, and creativity are declared the three most important skills needed for the future of employees. To find an answer to the question of what direction the future university education of production engineers should take, it is important to listen to the suggestions of manufacturing companies about what skills industry needs and what it expects from its engineers in the future. Higher education institutions need to work closely with industry, government agencies, and student/ alumni organizations to stay abreast of emerging competency requirements. The adoption of Industry 4.0 at higher education institutions depends on many factors.

These include staff readiness, student understanding, infrastructure, availability of skilled workers, training programs, access to the Internet, collaboration with industry, etc.

Industry 4.0 promotes the idea that workers will increasingly focus on creative, innovative and communicative activities. Routine and supervisory activities will be replaced in whole or in part by automated systems. To achieve these goals, the key skills required for I4.0 professionals are categorised into 3 broad groups, as shown in Table 1: personal, social and professional competencies. Personal competence can be understood as the ability to act reflectively and autonomously, which includes the ability to learn independently (develop cognitive skills) and to carry a system of ethical values. It also includes the competence to generate new knowledge and to be constantly alert in terms of innovation and creativity. In addition, managers must be able to change their leadership style, as the teams of the future will be very diverse in terms of culture, education and geographic location.

Social competence refers to the fact that an individual is placed in a social context that requires the ability to communicate, cooperate, and build connections and social structures with other individuals and groups. Full digital integration implies the automation of communication and collaboration, especially in connection with standard processes.

Professional competence refers to the range of different technologies, including IT tools, production, and automation. The worker is responsible for the larger scope of the process and must understand the relationships between processes and information flows. Automation concepts and technologies must be well understood, as well as digital thinking. Knowledge of computer information processing logic and how to translate qualitative information into quantitative form is required.

Table 1. Skills and competencies required for the I4.0 professional [7]

Skills and competencies	
PERSONAL COMPETENCIES	•Ability to learn •Ability to act in an autonomous way •Creativity/Competence of innovation generation •Ability to interact with modern interfaces •Adaptability / Ability to change
SOCIAL COMPETENCIES	• Continuous Improvement • Personal responsibility • Holistic thinking / strong analytical thinking • Organization • Judgement • Communication skills • Cooperate • Establish social connections • Ability to take individual or socially constructed ideas to action • Thinking in an organizational level • Teamwork abilities / heterogeneous interdisciplinary and interorganizational teams • Leadership skills
PROFESSIONAL COMPETENCIES	• Competence of computer programming / IT knowledge • Competence of digital thinking/digital skills • A skill of highly-intellectual activities • Ability to use domain knowledge (methodologies, languages, and tools) for a job or specific task • Deep understanding of interrelations among electrical, mechanical, and computational components will be a vital ability / Interdisciplinary knowledge • Organizational and processual understanding (relations between processes and information flows, possible disruptions as well as potential solutions) • Problem solving • Widely spread expertise

The list of skills and competencies required in I4.0 is extensive and therefore training should promote lifelong learning.

Excellence in education must be achieved through interdisciplinarity, because without interdisciplinarity there is no innovation. The development of complex socio-technical systems requires the collaboration of different academic disciplines. Future engineers need skills that enable them to "think outside the box" and adapt quickly to rapid innovation cycles. In times of industrial revolutions, such as I4.0, revolutionary innovations that are characterized by something "truly new" dominate, with a strong impact on society on a global scale. Innovation comes from fresh minds.

It is obvious that the half-life of the knowledge sector is getting shorter and shorter and that students do not need knowledge with specialized content so much as the ability to learn for life. They need to acquire the skills to adapt to change. Regardless of specialization, production mechanical engineers in manufacturing must have a basic knowledge of multidisciplinary areas. The future of industry, especially in the context of I4.0, is closely linked to IT technologies at all levels of production. The survival of future engineers in Industry 4.0 will require above all the possession of IT skills, as IT is a key driver of innovation in future industrial contexts. Future engineers must be able to "speak code" because we already live in a world where everything and everyone is networked (Big Date and Cyber Physical Systems). Training in information and communication technologies is necessary to ensure knowledge and skills development in future generations of engineers. The skill of analytical learning is also very important, which provides a new understanding of the learning process. Only Big Data can produce "intelligence." So, by applying analytical thinking, intelligent (meaningful) data is obtained from a large amount of data, based on which intelligence is accumulated from information segments, which is the starting point for artificial intelligence. Scientific programming is increasingly becoming part of mechanical engineering or, as many say, the "new Latin for engineers," Figure 2.

Future engineers should also be trained in new business thinking so that, in addition to the basic skills for managing development projects, they acquire additional skills, especially in management and decision making. They need to know how to communicate business ideas to various stakeholders, i.e., they need to know how to collaborate in the "global village". Future engineers need to be fearless and able to adapt quickly to change through comprehensive skills. They need the ability to critically assess problems and develop sound, responsible and creative solutions.

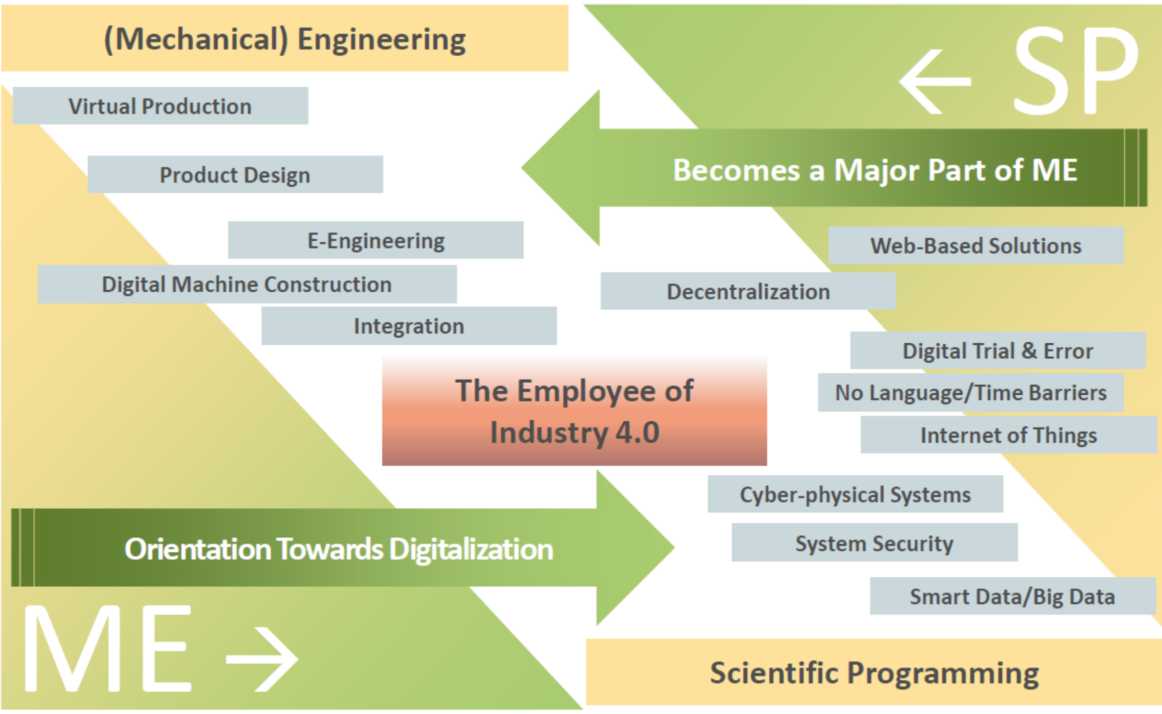

Fig. 2 Mechanical engineering and scientific programming [3]

3. WAYS TO ACQUIRE THE SKILLS NEEDED FOR INDUSTRY 4.0

Of particular interest is the question, "What is the best way to acquire the skills needed for Industry 4.0?" In recent years, a large number of papers have been published on education in the context of Industry 4.0. Some of the papers focus on new qualification requirements, others emphasize specific areas that should be included in curricula, the third group focuses on transforming education itself in ways similar to industry, and the fourth group focuses on developing new laboratory concepts that allow students to experience an Industrie 4.0 like manufacturing environment [4].

The new qualification requirements in the age of Industry 4.0 include: interdisciplinary thinking, decision-making and problem-solving, cultural and intercultural competencies, and lifelong learning. The biggest challenge is to train employees to successfully implement a Cyber-Physical System. Cyber-Physical Systems and

"Industry 4.0" require future engineers to deal with Big Data and complex, multidisciplinary problems, as well as to collaborate with machines in "hybrid teams." To meet these requirements, future production engineers, as well as their professors, must acquire new skills and qualifications. The increased need for flexibility, cooperation between universities and industry, and open learning systems (online learning platforms, freely accessible courses - "open university") was highlighted. Universities around the world are already using various teaching methods to educate engineering students for Industry 4.0, including: Learning Factory, Project-Based Learning, University-industry partnership, Problem-Oriented Scenarios, Scenario-Based Learning, Simulation Game, Problem-Based Based Learning, Work-based learning, Flipped Classroom, e-learning / m-learning [5].
Papers discussing which areas are of great importance for Industry 4.0 and which should be included in the curricula, the important role of artificial intelligence is highlighted in particular. In addition to this area, the importance of mathematics, computer science, natural sciences and technology is also highlighted. It is necessary to introduce new courses composed of programming languages, statistical analysis methods, database systems, machine learning, control and security systems, and industrial robotics. Universities and professors must be open to new curricula and have the skills to implement them.
Numerous papers deal with ways to reshape education itself according to the principles of Industry 4.0. They emphasize the role of digital media and the individualization of education, especially in the area of vocational training. Engineering education in the age of Industry 4.0 is inconceivable without its connection to practice and practical work. Curricula must be flexible to allow, for example, their shortening or extension according to the individual needs of the student. Education must be designed intelligently and individually. Big Data technology is the gateway to a new way of supporting individualized learning processes for all. The challenges of future teaching and learning must be turned into opportunities for change [6].
A particularly interesting way to adapt education to the vision of Industry 4.0 is to develop new laboratory concepts for engineering students. It is very important to develop such laboratory concepts for students who do not come from the IT field, such as students of production engineering, using "simulation games." By incorporating real industrial technologies such as ERP systems and barcodes / RFID chips, an environment can be created that is roughly equivalent to Industry 4.0. Traditional labs need to be upgraded with visualization software tools, simulators and other equipment needed to implement Industry 4.0 in the real world.
One of the concepts involves the development of laboratories called "Learning Factories".

3.1. Learning Factory

The Learning Factory is a form of collaboration between industry and education whose goal is to improve the educational process and produce world-class engineers. The learning factory emerged from the needs of those involved in the educational process (industry, universities, students) and integrates hands-on curricula and factories where products are manufactured. The term "learning factory" is often used together with the term "teaching factory" by researchers and practitioners, so these two terms can be considered synonymous. The essence of the learning factory is that students from different engineering disciplines work on projects for industry customers to find a comprehensive solution to a problem or to implement specific innovations. Through project work and real-world problem solving, students apply the knowledge, methods, and tools they have acquired during their previous education, and direct contact with customers helps them develop their leadership, management, and communication skills. Improving students' competencies and providing hands-on access to education is what stands out as the main goal of the Learning Factory. The aim of the learning factory is to create an environment for learning and transferring theoretical and analytical knowledge and practical experience, as well as to facilitate the learning process itself through a strong connection with practical problems. Because they significantly reduce the gap between the competencies required by the manufacturing sector and the profile of engineers resulting from academic training, learning factories are considered a very successful model of collaboration between industry and academia, with a very positive impact on student performance through traditional ex-lectures. Learning factories are environments that realistically replicate certain aspects of the real factory, but at the same time remove elements that may burden students in acquiring knowledge and gaining experience in product planning, production, logistics and process management [7].
Learning factories are an important way to practice the technical knowledge associated with the development of the concept of Education 4.0. Education 4.0 takes into account, on the one hand, the use of developed technologies (e.g., advanced visualization techniques that integrate virtual reality) to facilitate the teaching process and, on the other hand, methods and workshops that introduce ambitious engineers to these technologies, such as working in Industry 4.0. With the technological progress, this educational concept becomes more and more a necessity. More specifically, faculties are trying to find new ways to combine theoretical knowledge in their faculties with real cases and implementation of CPS in industry, creating a situation where both sides will win.

4. CONCLUSIONS

The working world of I4.0 is looking for engineers who are interdisciplinarily trained and practise-oriented. Future engineers will increasingly have to deal with an automated, virtualized, more networked and flexible world. It is therefore very important to adapt engineering curricula to these requirements. Engineering education must be continuously developed in line with current and future industry requirements. Companies are looking for engineers with practical experience in industrial environments who can apply theoretical knowledge to real industrial problems.

The effective involvement of mechanical engineers in Industry 4.0 requires that they have the following competencies: knowledge and competencies related to computational and simulation technologies, understanding of product lifecycle phases, understanding and competencies related to planning and project management, and competencies related to teamwork.
Skills for I4.0 include not only technical / engineering and specific knowledge and competence areas, but also meta-skills independent of knowledge areas, such as critical thinking, creativity, communication and intercultural collaboration. Future production engineers must demonstrate competencies in the technical, professional and global fields.

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REFERENCES

[1] Gueye, M., Exposito, E. (2020). University 4.0: The Industry 4.0 paradigm applied to Education. *IX Congreso Nacional de Tecnologías en la Educación*, Puebla (Mexico), France

[2] Beke, E. (2020). The relationship and interaction between Industry 4.0 and education. *Műszaki Tudományos Közlemények,* Vol. 13, October 2020, 36-39, eISSN: 2601-5773

[3] Jeschke, S. (2016). Engineering Education for Industry 4.0 - Challenges, Chances, Opportunities. *CDIO European Regional Meeting*

[4] Coskun, S., Kayikci, Y., Gencay, E. (2019). Adapting Engineering Education to Industry 4.0 Vision. *Technologies*, Vol. 7(10), doi:10.3390/technologies 7010010

[5] Yoshino, R. T., Pinto, M. M. A., Pontes, J., Treinta, F. T., João F. Justo, J. F., Santos, M. M. D. (2020): Educational Test Bed 4.0: a teaching tool for Industry 4.0. *European Journal of Engineering Education*, DOI: 10.1080/03043797.2020.1832966

[6] Jeschke, S., Heinze, U. (2014). Higher Education 4.0 – Trends and Future Perspectives for Teaching and Learning. *64. DHV-Tag Virtuelle Lernwelten in der Universität Frankfurt am Main*

[7] Mourtzis, D. (2018). Cyber-Physical Systems and Education 4.0 –The Teaching Factory 4.0 Concept. *Procedia Manufacturing,* 23, 129–134.

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INTELLIGENT WELDING IN CONTEXT OF INDUSTRY 4.0

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Abstract: *Welding is analyzed here as an intelligent process in the context of Industry 4.0, with a focus on two aspects: automatization and machine learning. In the case of automatization, starting from the first industrial robots as applied in spot welding in car industry 50 years ago, advances in other welding processes like Gas Shielded Arc Welding (GSAW) and Laser Beam Welding (LBW) are presented. As for the machine learning, starting from the early efforts to use neural networks to correlate input welding parameters with a shape of a welded joint in early nineties, advances in modern machine learning technologies to predict mechanical properties and microstructure are presented.*

Keywords: *welding; industry 4.0, machine learning, neural network, automatization*

1. INTRODUCTION

Modern technological advancement leads to a need to develop more accurate and efficient means of achieving optimal welding parameters, for the purpose of monitoring and improving welded joint quality, without any welding defects [1-4]. The very concept of Industry 4.0 enables this approach to the welding process, through the automation of the process itself and the introduction of the concept of machine learning. Today people are in the latest age the fourth industrial revolution that is, in age Industries 4.0. Industry 4.0 based on the interrelationship of people and the latest technology. In the last few years, the world has been developing and implementing advanced technologies, especially digital technologies in the production processes of industry, and companies that want to stay in the market must monitor the development and modernize and automate their production processes to compete in the global market. Fundamental changes are brought about by digital technologies such as: introduction of the Internet, including open software platforms, open communications, open databases with powerful built-in processors, so that networked production in the industry becomes more flexible and efficient. Digital transformation represents the foundation of Industry 4.0 that characterizes transition to production-driven digital computers. Without digital transformation it would not have come to automated processes that are the foundation of Industry 4.0 thus gaining new insights and ways of managing production. The fourth industrial revolution is based on innovative technological solutions whose implementation in the field of development of production processes contributes to the evolution of technology. Continuous digitalization of production functions and processes in the field of welding influences decision makers to proactively and strategically consider the possibilities of innovative solutions and guided by cost-benefit analysis to make timely and correct decisions that affect the efficiency of the process.

This idea will present the application of neural networks as one of the most popular techniques of artificial intelligence to semi-automatic welding of structural steels. Based on a neural network, developed the Neural Network Soft Sensor (in future text NNSS) application will define the expected mechanical properties of a welded joint, based on the input process parameters, this methodology was successfully applied to melting production and casting progresses [5, 6]. Constant improvement of this concept, based on neural networks, resulted in the possibility of implementation, i.e., this software based on neural network can independently provide optimal parameters for a given welded joint, based on previous input data. The input data for the software will be based on the welding parameters (such as current, voltage, weld speed, etc.), and the output will be the desired mechanical properties of the welded joint (Figure 1).

The goal of this study is to initially provide a technological solution, wherein Neural Network Soft Sensor (NNSS) would enable a quicker and easier way of adopting the adequate welding technologies for structural steels. By using the application which would utilize Neural network soft sensor software for the purpose of establishing the relation between mechanical properties of used materials (in this specific case structural steels) and

welding parameters, along with providing maintenance and update services, which will allow companies from this part of Europe to be competitive both in the regional and the global market.
In this way, the welding process itself would be significantly quicker, and the need for test welding, which represents the standard way of validating the parameters, would decrease due to the fact that neural networks would enable the software to obtain optimal parameters in a more effective and efficient manner, thus saving material costs and time.
This will also decrease the workload of the welders, who are currently in high demand, but low on numbers on our market. While similar technologies exist in the global market, there are no such solutions in the regional market.

2. TECHNOLOGY

Realization of this project idea will consist of five stages, which will improve the quality and efficiency of welded joints, with special focus on saving time, money, energy and materials [7-10].
Implementation of the first stage will result in the development of numerical models of test specimens, which will be performed with varied input parameters (mechanical properties of materials in the welded joints), followed by welding of plates made of structural steel S355J2 [11] (due to the wide application of such structural steels in mechanical and civil engineering industry, and the fact the welding is one of the best and most efficient ways of joining such materials), which will then be tested in order to verify the numerical results and define the input parameters for the Neural network soft sensor (NNSS). These numerical analyses will involve simulating heat input (which is directly influenced by other welding parameters) to a welded joint, and creating a database of results for various parameter combinations)
Input for the numerical simulations will be obtained from gathered pWPSs (preliminary welding procedure specifications – documents which define all of the necessary parameters for welding a specific work piece under specific conditions, using a specific combination of base and filler material and a specific procedure). A total of 108 pWPSs will be used for this purpose which will define the combination of relevant parameters: Current ((100-140A; 120-160A; 160-200A), voltage (18-22V;20-22V;22-26V) and weld speed (40-180 mm/min; 60-200 mm/min; 150-350 mm/min).
Following to the previously defined first stage, the second stage will include welding of plates, using Metal Active Gas welding procedure (denoted as 135) [12]. Electrode of commercial name VAC 60 [13] will be used as filler material, and the diameter of the electrode made of this material will be 1.2 mm. Parameter ranges (current, voltage and weld speed) were adopted in a way that ensures that heat input (which depends on all three) is always between 0.5 and 2.0 kJ/mm, a standard range of values for structural steels. Welding will be performed for on a total of 30 plates (24 of which will be used in the experiment, whereas the remaining 6 will be used as a reserve, in the case something is wrong with the first group) which will provide 12 welded joints (along with 3 spare ones), for the purpose of experimental testing which will verify the numerical simulations, since this number of plates will provide sufficiently accurate results.
The third stage would include the cutting of a total of 84 specimens from the 12 welded plates, for testing purposes – 7 specimens will be obtained from a single plate, 3 of which will be used for tensile tests, 2 for hardness and 2 for bending tests, in order to verify the numerical results, and thus obtain the input parameters for the software.
The fourth stage will include testing of these specimens, using both destructive (tensile, hardness bending) and non-destructive methods (radiography). Non-destructive testing will determine if there are any defects in the welded joint which may not be allowed in accordance with the standards, whereas destructive tests will provide the results for mechanical properties of the welded joint, which will be compared with the numerically obtained ones. If the comparison is favourable, i.e. the difference between the experiment and the simulation is sufficiently accurate (within 15% of each other) the corresponding combination of welding parameters will be used as input data for the NNSS application.
The fifth stage will involve the development of the software platform NNSS (intelligent soft sensor), whose core is a neural network. A neural network tasks consists of using the input values of welding process parameters to predict the expected mechanical properties, such as tensile strength, toughness and hardness. The developed NNSS will enable the user to input various combination of input parameters (welding parameters) and use them to determine the optimal mechanical properties for the welded joint in question (depending on its material, exploitation condition, etc.) shown on figure 1.

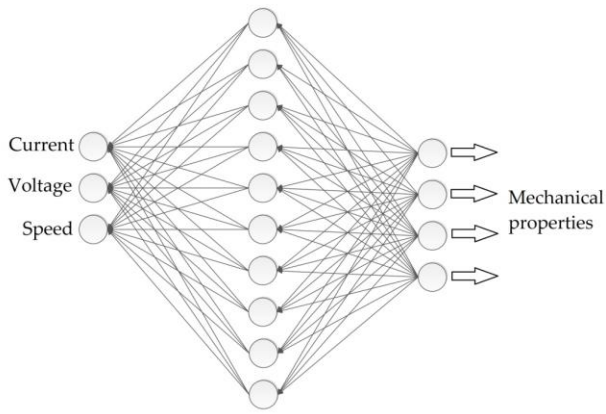

Figure 1:The input and output data for NNSS

Also, fifth stage will involve testing of NNSS using sets of experimental data which were not used in its development. Results obtained by NNSS prediction will be compared to the results which were obtained by experimental tests within the previously defined stages. This testing will be expanded by comparing the results obtained by NNSS software and finite elements method, which will be performed in ABAQUS software, using the finite element method, which have wide usage in modelling and calculating welded joints [14].
An additional benefit resulting from this project idea is reflected in its contribution to the relevant scientific fields – results obtained during its realization will be published

in scientific papers. What makes this contribution particularly important is the fact that this specific application of neural networks in welding is a very new field which is still largely unexplored. In addition, this type of solution is a new concept in the region and is likely to inspire other local companies and teams to get involved in application of neural networks in welding industries.

3. MARKET ASSESSMENT

Solutions based on neural networks are being developed and used in certain parts of the world, e.g. Sweden, India and Japan, however this concept is still rather new and unknown in Serbia and the region. In that sense, Neural Network Soft Sensor (NNSS) has the potential to establish itself as a groundbreaking technology in the regional market. It should be taken into account that foreign companies are also present in the aforementioned market, thus there is a strong possibility of expanding our business on the global market, which is our intention in the later projects which could result from this initial project idea. This project idea will provide customers with a very simple and user-friendly way of searching and selecting of adequate parameters, while saving considerable amounts of time and materials for the company which is using our software.

Welding is widely used in various industrial fields, particularly in mechanical and civil engineering. The most important aspects of these industries in the regional market include energy production, thus our focus will be on storage tanks, pipelines, hydropower and thermal plant equipment and various structural elements related to them.

Ideal customers for this innovative method include small, medium and large entrepreneurships which are involved in various fields of work and provide the basis for constant improvement of welding technologies.

An important part of project idea is implementation of its ability to generate profit in the future. The authors of this project idea thoroughly reassessed the possibilities of profit generation and concluded that the implementation of a breakthrough technology gives strong possibilities to improve market position and revenue potential. New technology puts the company in a favorable position compared to its competitors. Use of intelligent software eliminates the necessity for the following activities:

- Welding engineer analysis required a preliminary welding procedure specification (pWPS), which usually takes 40 work hours (the average cost being 20 euros per work hour);
- Base material, 3 sets of 2 plates (material cost for this steel and dimensions is 20 euros);
- Welding time, including the filler material, shielding gas and electric energy (around 5 work hours, with the rate of 10 euros/ hour);
- Welder's time (around 5 work hours, with the rate of 10 euros/hour);
- Non-destructive tests BW (VT, PT/MT, RT/UT - 42.55 euros)
- Destructive tests BW (Tensile and bending tests – at least one specimen per test, total of 51.91 euros).

Given that there are operating welding machines in any givenr company in Serbia, this software saves approximately about 50 hours of working time for the development of one pWPS.

In Serbia, a typical welding project last 3-6 months, wherein each new project requires defining and qualifying of new procedures, and one company has an average of four procedures per year. Taking into account that during these procedures, a typical amount of costs resulting from presence of defects is around 8000 EUR. This technology will significantly decrease these costs, while also saving the time of everyone involved, thus improving the efficiency.

4. CHALLENGE AND THE INNOVATIVE SOLUTION ADDRESSING IT

Problems which occur during welding of new materials require a lot of time and material in order to determine the optimal welding parameters, taking into account that every parameter combination requires the manufacturing and welding of its own test specimens. In addition, welders are subjected to excessive radiation, there is unnecessarily high power consumption, and significant amounts of waste materials are produced. This is a commonly encountered problem in the industry, which we determined from personal experience.

In addition, the processes described above are time-consuming and costly, which is another factor which can be significantly improved by this solution.

Another advantage of this solution is that it can use predefined welding parameters to determine if their combination will provide satisfying results, in other words it could prevent the applications of welding technologies which could require additional repairs (resources, time and effort). In the figure 2 below is given a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, done as part of identifying strengths, weaknesses, opportunities, and threats related to development this project idea. Strengths and weaknesses are usually considered internal, while opportunities and threats are usually considered external factor.

Another challenge is to protect all intellectual property resulting from this study, mainly the software which will rely on neural networks, via patent, in accordance with the intellectual property protection laws and regulations. According to these regulations, it is possible to patent software in the case it is a part of an innovative solution which has industrial application, and NNSS falls into this category. All IP resulting from this project belongs to the project team, NNSS weld, and the project does not require the use of third-party intellectual property. The initial plan for this project idea is to submit an application for a national patent, which should be a simple procedure, due to lack of competition in the local market. As for the International patent, additional state-of-the-art analysis will be required, since some slightly similar solutions already exist in other regions, such as North Europe and Asia.

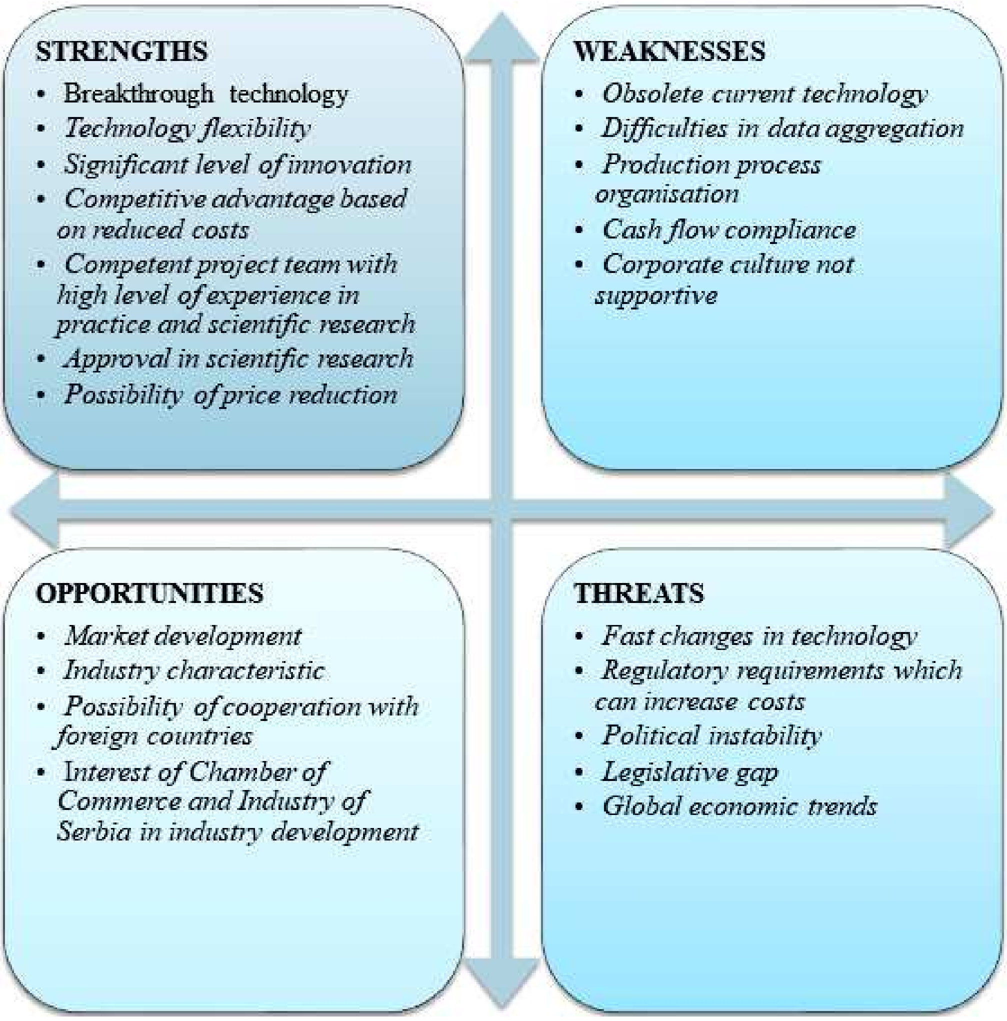

Fig. 2. SWOT analysis

5. DISCUSION AND CONCLUSION

Development of the Neural Network Soft Sensor for the purpose of automatic selection of optimal process parameters, this solution will provide increased welded joint quality, and welding processes optimized in this way would lead to lower electricity consumption and better protection of the environment and welders alike. All of this will result in buyers achieving significant savings in terms of materials, energy and time consumed during the new welding technology adoption process, thus providing financial, practical and health benefits to all parties involved.

Advantage in the regional market is the fact that there are no existing solutions related to the same problem as the one this study imply for solving, since no companies in the region are involved in using Neural Networks as a means of improving of welding procedures.

Estimate is that it will take about a year to properly develop this study develop in project, wherein the first stages will be focused on the development of the prototype, which should provide the initial, basic version of the software. The next stages will focus on improvements in order to obtain the final, working version. The refunding should start from the moment it enters the market, since there is no competition in the region. In order to break even, it will be necessary to get around fifty companies in the region and abroad as customers. It is expected to find between ten and fifteen companies every year.

The initial version resulting from the project will represent a working prototype which will be additionally improved, hence it is expected that our product will start generating profit after 5 years.

An important part of this project's idea is development the possibility to achieve profit in the future. After a detailed analysis of the current state of the regional market, it was concluded that the application of the innovative technology like this would provide competitive advantage over other companies, since none of them offer this kind of service. This results in increased stocks values, increased income and the possibility of further development within the welding industry. The use of Neural network soft sensor Weld application will achieve considerable savings, i.e. it reduces the need for adopting new technologies by using the trial and error method, since optimal welding parameters can be determined with a single test. The traditional system can be time-consuming (over 50 working hours), and with the material used, can exceed 1025 euros in costs. Each time another error is made, the next attempt will cost an additional 1025 euros.

In conclusion, this solution will save at least 1025 euros and 50 work hours whenever a new technology is being adopted. Additionally, welding technologies are widely used in various industries, but there is a shortage of available welders. This solution will allow them to work more efficiently and productively, due to time saved by eliminating the need to test every welding parameter combination.

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REFERENCES

[1] Aranđelović M., Sedmak.S., Jovičić R., Perković S., Burzić Z., Đorđević B., Radaković Z., Numerical simulation of welded joint with multiple various defects. Structural integrity and life, 2021. 21(1): p. 103-107.

[2] Aranđelović M., Sedmak.S., Jovičić R., Perković S., Burzić Z, Radu D., Radaković Z., Numerical and Experimental Investigations of Fracture Behaviour of Welded Joints with Multiple Defects. Materials, 2021. 14(17): p. 4832.

[3] Aranđelović M., Sedmak.S., Jovičić R, Sedmak A., Radaković Z., Finite element analysis of efects of multiple defects on welded joint integrity, in 8th International congress of Serbian society of Mechanics. 2021: Kragujevac, Serbia. p. 172 - 173

[4] Aranđelović M., Sedmak.S., Jovičić R, Kozak D., Đorđević B.. Numerical simulation of crack growth in a welded joint with defects, Procedia Structural Integrity. in Procedia Structural Integrity. 2021.

[5] Dučić, N., et al., Application of Machine Learning in the Control of Metal Melting Production Process. Applied Sciences, 2020. 10(17): p. 6048.

[6] Dučić, N., et al., Casting Process Improvement by the Application of Artificial Intelligence. Applied Sciences, 2022. 12(7): p. 3264.

[7] Tanasković D., Đorđević B., Aranđelović M., Sedmak S., Sedmak A., Đukić M., Tatić U., Repair Welding of Crane Wheels in Steelworks Smederevo, in 8th International Conference on Innovative Technologies for Joining Advanced Materials (TIMA 16). 2016: Timisoara, Romania. p. 180-185.

[8] Tanasković D., Đorđević B., Gajin M., Aranđelović M., Gostović N., Damages of burner pipes due to the working conditions and its repair welding, in ECF22 - Loading and Environmental effects on Structural Integrity. 2018: Belgrade, Serbia. p. 404-409.

[9] Tanasković D., Đorđević B., Sedmak S., Aranđelović M., He effect of exploitation conditions on the damage of a roller reducer toothed shaft and its repair Machine Design, 2018. 10(4): p. 147 - 162.

[10] Aranđelović M., Milovanović N., Đorđević B., Sedmak S., Martić I., Reparation, inspection and damage analysis of steam boiler. Welding & Material Testing, 2020. 3: p. 9-12.

[11] SRPS EN 10025 Hot rolled products of structural steels. 2020.

[12] SRPS EN ISO 4063:2013 Welding and allied processes - Nomenclature of processes and reference numbers.

[13] Elektrode-Jasenice, Dodatni materijal za zavarivanje. 2010.

[14] Sedmak S., Jovičić R., Sedmak A., Đorđević B., Čamagić I., Numerical analysis of different weld geometries of lap welded joint in ammonia transport tanks. Structural integrity and life, 2017, 3(17) , p. 217 -220

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IMPLEMENTATION OF CLOUD TECHNOLOGY IN THE FIELD OF PREDICTIVE MAINTENANCE 4.0

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Abstract: *According to the Industry 4.0 concept (I4-concept), the main carrier of production processes is "smart" production, which is located in a "smart" factory. This production is characterized by complete digitalization of all production processes as well as a very high degree of automation and robotization. Hence, the structure of "smart" production is quite complex. The basic parts of its structure are: Internet of Things (IoT), cyber-physical systems (CPS), the necessary supporting infrastructure that ensures the smooth operation of all elements of "smart" production and the necessary technologies that manage, monitor and control all processes. (Network Technology and Protocols, sensor networks, Cloud Computing and Big Data). In order for "smart" production as a highly automated system to be constantly operational, it is necessary to introduce "smart" maintenance as an accompanying segment, which will monitor the operation of the system and keep it operational all the time. For this reason, this paper will present the practical implementation of Cloud technology in the field of monitoring the state of machine systems. The Optime device, manufactured by Schaeffler from Germany, is treated as a practical example. This device is one of the intelligent devices that are an integral part of the infrastructure in the implementation of Cloud Computing in the field of monitoring the state of machine systems.*

Keywords: *Smart production; Cloud computing; Predictive Maintenance; Optime*

1. INTRODUCTION

The fourth industrial revolution (Industry 4.0) represents the general digitalization of business processes, and maintenance is one of them [1,2]. The concept of the fourth industrial revolution affects not only business processes, but also the overall way of life. More precisely, Industry 4.0 is a paradigm that unites all segments of human life.

The paradigm itself, as the main carrier of production processes, proclaims a "smart" factory that is becoming a general synonym for value creation. The main characteristics of the "smart" factory are the digitalization of production processes as well as a high degree of automation and robotics. By synthesizing the mentioned characteristics, "smart" factory ("smart" production) becomes a very complex ecosystem whose main structural elements become: Internet of Things (IoT), Cyber-Physical Systems (CPS), Virtual Reality (VR), Augmented Reality (AR). Extremely high precision, flexibility, high quality and reliability are expected from all the mentioned structural elements. All these requirements are controlled and monitored in real time, so it is necessary that the entire system has adequate infrastructure, which in addition to networking and connecting elements of the ecosystem will have the task to ensure proper and smooth operation of all structural parts. For this reason, appropriate technologies are being introduced, such as: network technologies and protocols, sensor networks, Cloud Computing and Big Data.

Taking into account the very serious requirements that the I4-concept places on the "smart" factory, it can be concluded that it is necessary to introduce another accompanying but very important part into the Industry 4.0 paradigm, and that is the maintenance of machine (production) systems. Since all production processes take place in real time, this future maintenance must be permanent and must give results also in real time, because any greater delay in feedback (status) information could cause a major error that would be due to the high degree of process automation. spread at high speed throughout the system.

Maintenance is necessary because it prolongs the life of the device. The most common forms of maintenance of machine systems are corrective and preventive. Corrective maintenance is a maintenance approach that is performed when there is already a loss of functionality of a machine element. This type of maintenance can often lead to emergency delays that cause a large loss of time to repair the fault, but also significant financial losses due to downtime of one part of the production system. Preventive maintenance means planned downtime of machine systems activities that will keep the system in working order, which increases the availability of the system., maintenance should be planned in advance with an accurate estimate of the period of failure of the machine to reduce the risk of accidents, financial losses and casualties. Paradigm Industry 4.0 envisages permanent monitoring of the state of the system on the basis of which it is possible to accurately determine whether there is any damage and if there is, its impact on the functionality of the system can be monitored over time. This type of maintenance, which involves 24/7 monitoring of the system, which is supported by extremely sophisticated hardware and software, is called Predictive Maintenance 4.0 (PdM 4.0). Predictive maintenance (PdM) is commonly used in various sectors, such as manufacturing [3], automotive [4] and aerospace [5]. Predictive maintenance can detect equipment failures and predict failure times in advance using data analysis tools and statistical inference approaches [6]. Moreover, with PdM, the time of the next failure can be predicted in a precise way [7,8]. The main goal of PdM is to identify initial failures and subsequent deterioration of component development using previously acquired information. Therefore, previous activities are considered in determining further maintenance procedures [9].

2. THEORETICAL BACKGROUND

2.1. Predictive maintenance

Predictive maintenance is a modern type of maintenance that is a combination of different techniques and methods with the aim of detecting various defects of machine elements at the earliest possible stage. The best example of this is the predictive maintenance of rotating machine elements. A roller bearing can be used as a representative.
Rolling bearings are transmission machine elements that are in the structure of almost every machine system. Due to their construction, but also the nature of the function they perform, they represent one of the most sensitive parts of the machine system. In a large number of cases, bearing damage occurs as a result of damage to another machine element (e.g. shaft misalignment, imbalance, excessive belt tension, loose machine stand, poor lubrication, etc.). The initial damage that occurs on the roller bearing is most common in the form of microcracks that are difficult to see with the naked eye. In addition, the location of roller bearings is usually such that they are more difficult to access. For this reason, predictive maintenance is very suitable for monitoring the condition of roller bearings, which has the ability to detect damage at an early stage. In addition, the condition of the roller bearing is designed so that it is not necessary to open the machine, but the measuring instruments can be placed on the housing itself, which greatly facilitates the installation of the necessary measuring devices.
The installed measuring equipment is now in a certain way connected to the computer on which the obtained results are processed and visualized through certain software. In addition, predictive maintenance includes special expert programs that can use data processing to determine the exact condition of the observed roller bearing as well as monitor the progress of the identified damage. Special software tools enable the speed of progression and spread of damage as well as the assessment of the moment when the damage will become so great that it will cause the loss of operational function, based on the results or measurements performed permanently.
In short, this type of maintenance provides the possibility of predicting the moment of failure of a machine element, which further allows a timely planned shutdown of the machine system to repair or replace the damaged part. This completely eliminates the possibility of an emergency stop, which is the main advantage of this type of maintenance. In fig. 1 shows the appearance of the roller bearing vibration measuring device.

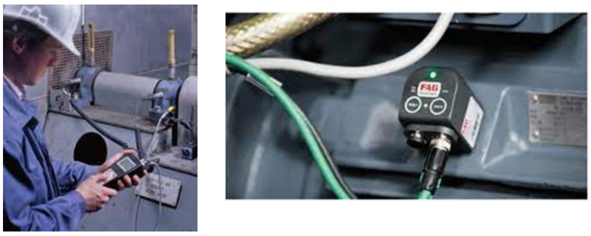

Fig.1. Vibration measuring devices for roller bearings: Offline measurement (left)[10]; Online measurement (right) [11]

The traditional way of measuring the vibrations of roller bearings is usually focused on the so-called. offline measurement (Fig. 1-left). This type of measurement is not so reliable because it is carried out periodically, so it leaves the possibility that potential damage will progress over time and cause an emergency stop. In that case, a pre-made measurement plan is desirable, which should contain an evenly distributed sufficient number of predicted measurements in order for the obtained results to be as authoritative as possible, thus obtaining a more realistic picture of the observed machine element (e.g. roller bearing).
On the other hand, there is the so-called online vibration measurement (Fig. 1 - right) which takes place permanently 24/7. This is the option chosen as the future way of measuring the vibrations of machine elements. The main feature of this method of measurement is that the data is recorded all the time in real time and the same through a certain infrastructure can be sent to the place where with the help of expert software will be processed and visualized results. Also, this method of measurement gives the possibility to be relatively easily implemented in an automated measurement system so as to expand the possibilities of monitoring the state of the machine element in the sense that through certain components, e.g. PLCs can set alarm thresholds that will be activated by maintenance personnel. With the activation of the I4-concept, it went a step further where, for example. machine learning used for fast training of vibration measuring devices, so that the measuring device, when installed on a machine system, first learns, i.e. "remembers" the operating parameters of the system and then sets the alarm thresholds that are far simpler for communication between machine and man (meaning alarms).

2.2. Cloud computing

Paradigm Industry 4.0 and with it the I4- concept are based on process digitization. Undoubtedly, therefore, a greater focus will be on infrastructure as well as technologies that will have to be created to meet all the upcoming requirements of the I4-concept, such as. high speed, significantly higher network power, significantly higher IP addresses, system stability and reliability, system security, etc. In accordance with the requirements set, the IT industry began to design and create new technologies that can meet the required performance. Over time, certain technologies develop to the extent that they become the subject of research for themselves, such as: Cloud Computing, mobile technologies, sensor networks, etc. In addition, there is a new concept in the field of mass data processing, the so-called. Big Data.
In this paper, the focus is on Cloud Computing as well as its implementation in the field of predictive maintenance. As it is known, Cloud Computing is the provision of services to a heterogeneous group of end users through the delivery of stored capacity and computing resources. The physical interpretation of Cloud Computing can be formulated as the sharing of resources over a network (usually the Internet). The principle of Cloud Computing is based on the use of data and software located on servers in a remote location that are accessed through browsers or mobile applications. Based on this, it can be unequivocally concluded that Cloud technology offers a great deal of flexibility and mobility during operation. These benefits have been successfully used for the practical implementation of predictive maintenance in "smart" factories.
The technology itself gives the end user options that he can combine and thus optimizes the resources necessary for his business activities. For this reason, Cloud Computing offers three options: Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). Taking into account the above models, it is possible to implement Cloud technology in predictive maintenance. The technical solution for this implementation was patented and published by the German manufacturer Schaeffler under the name "Optime".

2.3. Communication (Machine to Machine M2M)

One of the basic conditions of the I4- concept is the highest possible degree of process automation. This condition also applies to the automation of communication between devices or "intelligent" things. As a mechanism for fulfilling this condition, the so-called M2M communication. This communication is a network of "intelligent" things that can communicate with each other or communicate with the global network without human help.
M2M communication is performed using M2M networks which are divided into: full IP (Internet Protocol) and hybrid networks. For the implementation of Cloud Computing in predictive maintenance, hybrid networks are more suitable, which are the basis of the technical solution of the mentioned "Optime" device. By definition, hybrid networks consist of several integrated nodes that communicate with each other. A typical representative of a hybrid network is the so-called MESH network (Fig.2).

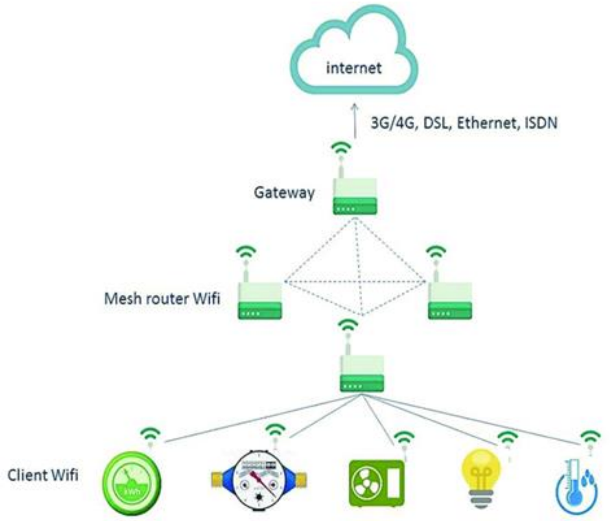

Fig.2. MESH network [12]

In fig. 2 it can be seen that the MESH network consists of several integrated nodes that are wirelessly interconnected with each other. Each node represents a Wi-Fi access point. The main feature of this network is that it maintains connectivity even in the event of a failure of one of the nodes in the network. This feature is used for implementation in predictive maintenance because it provides additional stability of the Optime device. In addition to nodes, an integral element of the MESH network is the gateway. The function of the gateway is to consolidate the signal to the IP network. In addition, it can filter, store and process them before sending them to the network [13].

3. IMPLEMENTATION OF CLOUD COMPUTING IN PREDICTIVE MAINTENANCE

3.1. Optime device

The implementation of Cloud Computing in predictive maintenance was in practice performed using a new generation device "Optime", of the German manufacturer Schaeffler. The device itself is a highly sophisticated product that is simple in construction and easy to place on the measuring point. It should be noted that it is one of the intelligent devices that are designed to monitor the state of the system (elements) by monitoring vibrations. It is specifically intended for measuring and monitoring the vibrations of rotating elements such as e.g. roller bearings, shafts, rotors, etc.
The device itself is a combination of existing instruments (sensor and vibration meter) that are connected by additional elements that ensure communication of the device with another similar device but also with the gateway through which the device has an Internet connection. The principle of operation of this device is

based on the MESH network. In the physical interpretation of "Optime", the device is one of the nodes of the MESH network. The appearance of the "Optime" device is given in Fig.3.

Fig.3. OPTIME device [14]

The basic components as well as the principle of operation of the device are given in Fig. 4.

Fig.4. Basic components of "Optime" device [15]: 1- sensors; 2- Gateway (receiver / transmitter); 3- digital service

The principle of operation of the device consists in the fact that the sensors located at the measuring points of the device under monitoring, collect information on the magnitude of vibrations.

The collected data will be transferred via the MESH network to a gateway that consolidates the signals received from the sensor and then sends them to a digital service located in the cloud. This way of working is a typical example of the implementation of Cloud technology in the process of monitoring the state of the machine system.

3.2. Predictive maintenance system architecture

Based on Fig. 4, the architecture of the system for monitoring the state of the machine system in which Cloud technology is implemented can be set. For easier explanation in fig. 5. a simplified presentation of the architecture of the predictive maintenance system using the intelligent device "Optime" and Cloud technology is given.

In fig. 5 it can be immediately concluded that the predictive system based on Cloud technology of the modular type. Basically, four modules can be distinguished, which are interconnected and function as one whole. The basic module is level with sensors. It is also the level that is related to production processes, i.e. the level that is an accompanying part of production processes. For the specific case that is the subject of this paper, this level consists of sensors for measuring the vibration of rotating elements. However, for the context of predictive maintenance (PdM 4.0) in the I4-concept, the mentioned sensors were transformed into intelligent devices (things), so their networking resulted in a network of intelligent things (IoT), which is one of the main features of the Industry 4.0 paradigm. Transformation of the sensor into an intelligent device is achieved by adding the necessary electronic components that allow the sensor to communicate with other sensors with which it is networked, but also with the gateway, which is actually a connection between the sensor and the Internet or Cloud.

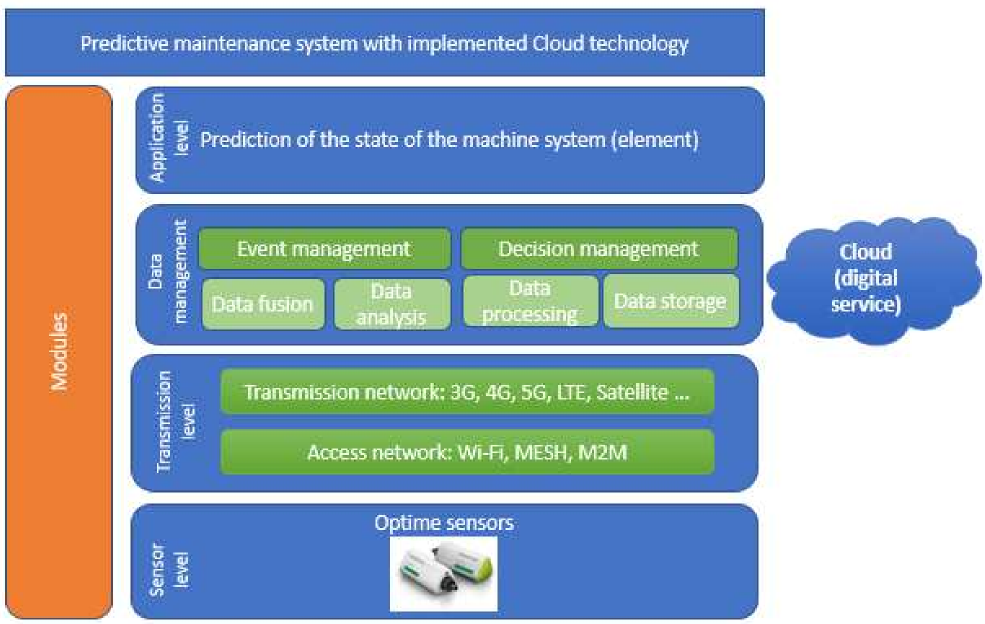

Fig.5. Predictive maintenance system architecture with implemented Cloud technology

The next level in the structure of predictive maintenance is transmission. It can be conditionally said that this level has its two sub-levels: access network and transmission network. In order for the IoT, i.e. for the observed case "Optime" sensors to be able to communicate with each other but also with the gateway, an access network is needed. For the observed case, it is a MESH network that combines sensors and a gateway. When the gateway receives signals from the sensor, it consolidates them and then sends them to the Cloud. Consolidated data is sent via the transmission network. The transmission network is actually a global network (Internet) which, depending on the case, can be 2G, 3G, 4G, and in the near future, 5G network is increasingly used, but also satellite transmission, etc.

The next level in the structure of predictive maintenance systems is data management. This level in physical interpretation belongs to the Cloud and actually represents the point of contact through which the implementation of Cloud technology in the predictive maintenance process was performed. At this level, two subsystems can be distinguished [16]:

- event management
- decision management.

Each of these subsystems has its own components that will be explained separately.

The event management subsystem consists of the following components [16]:

- data fusion
- data analysis.

Data fusion means merging and combining the data obtained from the sensor. Since there is a continuous monitoring of machine systems (elements), an extremely large amount of data can be collected in one hour, which needs to be combined into a whole for further processing. For this reason, the predictive maintenance system not only enters the domain of Cloud technology but also the Big Data concept. The collected data on the condition of an element can not only be used for predictive purposes in terms of maintenance, but their proper consideration and additional processing and analysis can provide additional very important information regarding the performance of the machine element and / or system. in this way it can perform additional optimization and even innovation of the machine element / system, which is also one of the very important directives of the Industry 4.0 paradigm. Once the data has been merged, it is possible to perform an analysis of the data. Since the sensors are mounted on different machines, it is necessary to perform analysis and classification of which data group belongs to which machine, which is important for further processing.

The data prepared in this way is ready for the second subsystem - decision management. The constituent components of this subsystem are:

- data processing
- data storage.

According to the above components, it can be unequivocally concluded that this system contains expert systems (software) for data processing (vibration signals) as well as stored systems (e.g. databases). Expert systems have the task of processing the obtained data using various software tools that have the ability to process the vibro-signal and its visualization in the time, frequency or time-frequency (time-scale) domain. Therefore, the basis of this component of the subsystem consists of software tools for: time-synchronized averaging (Time synchronous average), fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT), Wavelet transformation, Wigner – Ville distribution, etc. The output of this phase of data processing is the visualization of the obtained results which are ready to be stored in the database but also transferred to the end user. If damage to the element is identified, further monitoring will be carried out and it will be followed the impact on the proper functioning of the element (system) and also generates a trend which can be used for prediction of the moment of failure of the monitored element (system).

The final level in the structure of predictive maintenance systems consists of applications. In the Industry 4.0 paradigm, one of the technologies is the so-called mobile technology. This technology involves the use of mobile applications. Mobile applications are software designed to run on tablets, smartphones, or other mobile devices. For this reason, they are located in the last level (module) of the predictive maintenance system, because they represent a link between machine and man. Through them, the end user (responsible person in the maintenance service) has the ability to monitor the operation process and the state of the system. The application has the ability to visualize the results obtained, but also to display certain text messages that briefly generate the status of the monitored element (system). Through a message or a graphic display, the application conveys to the user accurate information in a language he understands whether the system is operational, whether any damage has been identified and where, to what extent the damage has progressed, when the necessary element overhaul needs to be performed (system) as well as system status alarms (correct operation status, pre-alarm and alarm).

In short, all the expertise needed to predict the state of the system is now housed in the Cloud, which provides real-time system monitoring, which is of great importance in the context of the I4- concept. In addition, this method of supervision is simpler, more efficient and cheaper compared to the classic method of monitoring, which requires the necessary equipment for data acquisition and trained staff, which certainly requires increased financial expenditures.

4. CONCLUSION

An important segment for the proper functioning of a smart factory is the maintenance of the machine system. In accordance with the principles of the I4- concept, it is necessary that the maintenance process be continuous and very precise in order to maximize the availability of machine systems at any time. For this reason, a new concept was introduced - predictive maintenance (PdM 4.0), which means the introduction and implementation of sophisticated technologies in the maintenance process. In support of this, this paper presents a technical solution of the German manufacturer Schaeffler, which allows condition monitoring of the rotating machine elements. The concept of this solution implies the implementation of Cloud technology, which is one of the leading technologies of the Industry 4.0 paradigm.

The paper focuses on the architecture of the new predictive maintenance system, which provides multiple benefits, of which the following can be distinguished: simple construction of the device, simple installation of the device on the measuring point, continuous monitoring of the element (system) 24/7, real-time results. significantly increased availability of machine systems, prevention of accidents, significant savings in terms of personnel and technical equipment (up to 50%), the ability to monitor systems remotely and hard to reach places, no prior knowledge required to install and use devices, Cloud technology offers digital service of professional diagnostics based on expert algorithms and machine learning that is available 24/7 through the appropriate application so that the right decision can always be made, easy expansion of the network of intelligent devices (sensors) for different users and needs, the device can use staff at initial or advanced level, use of expertise, etc.

REFERENCES

[1] Abidi, M.H.., Alkhalefah, H., Umer, U.: *Fuzzy harmony search based optimal control strategy for wireless cyber physical system with industry 4.0*., J. Intell, Manuf., 2021

[2] Maddikunta, P.K.R., Pham, Q.-V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T.R., Ruby, R., Liyanage, M.: *Industry 5.0: A survey on enabling technologies and potential applications*, J. Ind. Inf. Integr., 26, 100257, 2021

[3] Baruah, P., Chinnam, R.B.: *HMMs for diagnostics and prognostics in machining processes*. Int. J. Prod. Res., pp. 1275–1293, 43, 2005

[4] Prytz, R., Nowaczyk, S., Rögnvaldsson, T., Byttner, S.: *Predicting the need for vehicle compressor repairs using maintenance records and logged vehicle data*, Eng. Appl. Artif. Intell., pp. 139–150, 41, 2015

[5] Aremu, O.O., Hyland-Wood, D., McAree, P.R.: *A Relative Entropy Weibull-SAX framework for health indices construction and health stage division in degradation modeling of multivariate time series asset data*. Adv. Eng. Inform., pp. 121–134, 40, 2019

[6] Susto, G.A., Schirru, A., Pampuri, S., McLoone, S., Beghi, A.: *Machine Learning for Predictive Maintenance: A Multiple Classifier Approach*, pp 812-820, IEEE Trans. Ind. Inform, 11, 2015

[7] Malhi, A., Yan, R., Gao, R.X.: *Prognosis of Defect Propagation Based on Recurrent Neural Networks*, pp.703-711, 60, IEEE Trans. Instrum. Meas., 2011

[8] Yuan, M., Wu, Y., Lin, L.: Fault diagnosis and remaining useful life estimation of aero engine using LSTM neural network, *In Proceedings of the IEEE International Conference on Aircraft Utility Systems (AUS)*, 10–12 October, Beijing, China, pp. 135–140, 2016

[9] Ding, H., Yang, L., Yang, Z.: *A Predictive Maintenance Method for Shearer Key Parts Based on Qualitative and Quantitative Analysis of Monitoring* Data. IEEE Access, 108684–108702, 7, 2019

[10]http://margoserwer.nazwa.pl/margo2/uploads/katalogi/fag-detector.pdf, Accessed on 2022-03-08

[11]https://www.t-matix.com/en/schaeffler-und-t-matix-iot-fuer-predictive-maintenance-anwendungen/, Accessed on 2022-03-08

[12]https://www.researchgate.net/figure/WiFi-mesh-infrastructure_fig1_316266647, Accessed on 2022-03-08

[13]https://www.bpa.edu.rs/FileDownload?filename=53631f14-a9bd-46f2-ad65-496d308f2c59.pdf&originalName=IoT%20Predavanje%202.pdf, Accessed on 2022-03-08

[14]https://www.schaeffler.de/remotemedien/media/_shared_media_rwd/05_products_services_1/industrial_products_services/maintenance_products/optime/001918C2_16_9-schaeffler-optime-red-dot-award-slider-image-01_rwd_800.jpg, Accessed on 2022-03-10

[15] Schaeffler Technologies AG & Co. KG, (2020). Schaeffler OPTIME

[16] Gladović, P. Deretić, M.: Internet inteligentnih uređaja i pametni gradovi. *Novi horizonti- VII međunarodni simpozijum saobraćaja i komunikacija* 2019

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THE ROLE 4.0 REVOLUTION: COMPETITIVENESS AND SUSTAINABLE DEVELOPMENT

Brankica TODOROVIĆ

Abstract: *The fourth industrial revolution is aimed at creating smart products and overall production. In a dynamic business environment, businesses strive to use advanced materials, oil and gas exploration and renewable energy, which affects competitiveness and encourages sustainable development.*
The goals of the research in the paper are: analysis of the Global Competitiveness Index 4.0, the impact of Revolution 4.0 on sustainable production and economic development and policies and measures to encourage competitiveness and 4.0 revolution in Serbia.

Keywords: *4.0 revolution; competitiveness; sustainability*

1. INTRODUCTION

Industrial revolutions have economic, social and political changes in the environment and economic development.
The "Industry 4.0" concept was first published in an article by the German government in November 2011, as a high-tech strategy for 2020" (Zhou et al. 2015, p.1). Opportunities for sustainable production at the macro level indicated positive implications of new business models and closed-loop product life cycles on the reduction of negative impacts on the environment and society, while micro perspective gave an insight into the potential of Industry 4.0 for the labor market and customer well-being (Stock & Selinger, 2016). Industry 4.0 represents a new and powerful industrial wave with an orientation toward digital and virtual technologies and customer service (Lopez de Sousa Jabbour et al., 2018).
The industrial revolution can boost the competitiveness of national economies by increasing innovation and the use of ICT. The fourth industrial revolution represents potential but also brings certain problems in the context of sustainable economic development. Sustainable economic development includes a number of priorities and goals based on the development of a knowledge-based economy, increasing social welfare and sustainable use of resources. New national development priorities relate on rethink competition and anti-trust frameworks needed in the Fourth Industrial Revolution, ensuring market access, both locally and internationally.

2. INDICATORS OF THE COMPETITIVENESS

Competitiveness is a complex and multidimensional category that can be encouraged by the activities of different sectors, which is especially important in the conditions of dynamic and accelerated development in the conditions of the fourth technological revolution. One of the indicators of competitiveness is the Global Competitiveness Index, as well as the Global Innovation Index. The level of competitiveness expresses the capacity of the national economy to generate sustainable economic growth at the current level of development in the medium term. The Global Competitiveness Index shows the competitiveness of national economies as well as the potential for long-term economic growth. Based on the ranked 141 countries, Serbia took 72 positions in 2019. The best ranked countries according to global competitiveness are: Singapore, USA, Hong Kong SAR, Netherlands and Switzerland. This year, the value of the index is calculated by the new methodology IGK 4.0, the value of the index is 60.9, IGK is calculated based on 12 pillars of competitiveness and 98 indicators: institutions, infrastructure, ICT adoption, macroeconomic stability, health, skills, goods market, labor market, financial system, market size, business dynamics and ability to innovate (Table 1).
In 2021, according to the Global Innovation Index, the five most developed countries in the world were: Switzerland, Sweden, the United States, the United Kingdom and The value of the index of the most innovatively developed country, Switzerland, is 65.5; Sweden 63.1; USA 61.3; Great Britain 59.8 and Korea 59.3. Korea. Serbia took the 54th place out of 132 observed countries, with the value of the innovation index of 35 index points. The analysis of rank movements by year shows an improvement in the position compared to 2010 (101), and especially since 2018, when the rank is below 60 positions (Figure 1).

Table 1. The Global Competitiveness Index 4.0 framework

Enabling Environment	Rank Serbia	Market	Rank Serbia
Institutions	75	Product market	73
Infrastructure	51	Labor market	54
ICT adoption	77	Financial system	82
Macroeconomic stability	64	Market size	74
Human Capital	**Rank Serbia**	**Innovation Ecosystem**	**Rank Serbia**
Health	76	Business dynamism	54
Skills	55	Innovation Capability	59

Source: WEF, 2019.

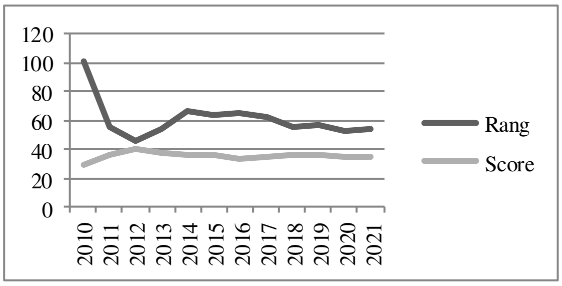

Fig. 1. Serbia's rank and score trends from the aspect of competitiveness

The Global Innovation Index includes seven pillars: institutions, human capital and research, infrastructure, market sophistication, knowledge and technology, business sophistication, creative results. The pillars that contribute the most to innovation in Serbia are: institutions (score 69.3, position 50), infrastructure (48.7; 44) and knowledge and technology (29.1; 43). Creativity has the lowest rank of all the pillars (76; 21.4) (WIPO, 2021).

Considering that Industry 4.0 represents a new and powerful industrial wave with an orientation toward digital and virtual technologies and customer service (Lopez de Sousa Jabbour et al., 2018), potentials for the progress of the 4.0 revolution in Serbia, in terms of competitiveness and innovation (technological backwardness) should be at a higher level.

3. OBJECTIVES OF SUSTAINABLE ECONOMIC DEVELOPMENT

There is more than one definition of economic development that is viewed in the context of sustainable development as a form of social and structural social transformation that respects the relationship between economic growth and non-renewable resources (Pearce & et al., 1989). A similar definition was given by the World Commission on Environment and Development, which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

The definition of sustainable economic development has emerged from the need for the international community to intervene to find ways to prevent the emerging ecological crisis. The United Nations General Assembly is therefore also addressing the issue of sustainable development and environmental protection. Thanks to the initiatives of this organization, conferences were held to discuss the issue of environmental protection and sustainable economic development.

The first UN Environment Conference was held in Stockholm from 12 to 16 June 1972. The Conference adopted the Environmental Declaration and the Action Plan for the Development of Environmental Activities. In the this documents, development is defined as a complex category that should provide conditions for well-being and preservation of the environment, while the goal of development is not only to improve material living conditions but also to attain moral and cultural values. The adopted Declaration on the environment outlines the principles: our planet has abundant and inexhaustible resources (Declaration of the Environment, 1972). The inexhaustible riches during the production cycles must be restored, and the exhaustive ones must be used in a way that will not threaten to exhaust them (Principles 3 and 5); for the social and economic development of man on earth, appropriate conditions must be provided for the quality improvement of his life (Principle 8), and during production it is necessary to use the achievements of science and technology in order to detect, avoid or limit environmental hazards (Principle 18).

In addition to these documents, the United Nations established the Human Environment Program (UNEP) in 1972 with the aim of directing public awareness of the growing threat to humanity from environmental degradation. The program should enable the prevention of air, water and the rational use of natural resources. In the following period, the following declarations and programs were adopted: the Declaration on Education and the Environment; Declaration and Recommendations for International Cooperation to Improve Living Conditions in Settlements; the Only One Earth program and more.

In 1987, the World Commission on Environment and Development submitted a report entitled "Our Future" which contributed to the conception of a new economic and environmental policy that would enable "sustainable development".

The European Charter for the Environment and Health was signed in 1989 by the Ministers of Environment and Health and the World Health Organization. With this Charter, the signatory states have committed themselves to strive to take the necessary activities to address environmental problems. These problems are related to ozone depletion and climate change, safe and adequate supply of drinking water in accordance with existing standards, chemical safety of food, environmental and health consequences of the impact of various sources of energy, traffic, the consequences of usage chemical of agricultural production, air quality, dangerous waste, biotechnology (especially genetically modified organisms) and clean technologies as preventative measures.

The United Nations Conference on Development and the Environment was held in Rio de Janeiro from 3 to 14 June 1992, at which the pursuit of sustainable development poses a new challenge and prerequisite for achieving global security. Environmental degradation is a kind of discrimination against man and restriction of his freedoms, and therefore solving environmental problems is becoming increasingly important as an essential issue for eliminating the unequal differences that exist in the world and within individual countries.

The Sustainable Development Goals (SDGs) were defined at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012. The objective was to produce a set of universal goals that meet the environmental, political and economic challenges which facing the world economies. Agreed by the United Nations, seventeen Sustainable Development Goals set the framework for addressing the most significant social, economic and environmental challenges by 2030. The Sustainable Development Goals of the 2030 Agenda officially entered into force on 1 January 2016, following the adoption of the UN Summit Resolution in September 2015. The 2030 Agenda is a global development Agenda beyond 2015. In the next 15 years, states parties are expected to mobilize all resources to would eradicate poverty, fight inequality and find answers to climate change. The Sustainable Development Goals, also known as the Global Goals, are derived from the Millennium Development Goals and address a number of societal needs including health, education, social protection and a healthy environment and climate resilient communities. The United Nations Millennium Declaration (2000) defined the fundamental values on which international relations in the 21st century should rest: freedom, equality, solidarity, tolerance, environmental protection and shared responsibility. The Millennium Development Goals are derived from this declaration. Since 2010, sustainable development has been built into the Europe 2020 strategy and is based on three pillars: "smart growth" with a focus on education and innovation; "sustainable growth" with low carbon emissions, resilience to climate change and environmental impact, and "inclusive growth" through job creation and poverty reduction. In addition to sustainable development goals, it is important for companies to be part of the digital economy, transforming their businesses in terms of digitization and innovation.

The 2030 Agenda with 17 Sustainable Development Goals and 169 targets covers a wider reach than the Millennium Goals and includes all three key dimensions of sustainable development: economic growth, social inclusion and environmental protection. Institutional development and cooperation which should ensure the rule of law and peace are also covered by appropriate goals and objectives. The Sustainable Development Goals are (United Nations, 2015):

Goal 1 No Poverty

• Under Goal 1, the new agenda implies the eradication of poverty in all its forms all over the world.

Goal 2 Zero Hunger

• Goal 2 has broad implications, which include ending hunger, enabling food security, improving nutrition, and promoting sustainable agriculture.

Goal 3 Good Health and Well-Being

• Ensuring healthy living and promoting overall well-being without regard to the age or place is what is meant by the formulation of Goal 3.

Goal 4 Quality Education

• The promotion of lifelong learning and providing opportunities for it, together with ensuring inclusive and equitable education for all, are the critical elements of Goal 4.

Goal 5 Gender Equality

• Due to the existing gender gap, stepping toward gender equality and the empowerment of all women and girls is the main direction of Goal 5.

Goal 6 Clean Water and Sanitation

• Making sure that water and sanitation are available to all and ensuring sustainable management of it is the core of Goal 6.

Goal 7 Affordable and Clean Energy

• In the light of climate change, resource scarcity Goal 7 places priority on providing access to modern energy, which is affordable, reliable and comes from sustainable sources.

Goal 8 Decent Work and Economic Growth

• Sustainable economic growth, employment at full capacity, and high productivity and insurance of decent working conditions for all are the key elements for Goal 8.

Goal 9 Industry, Innovation, and Infrastructure

• Establishment of resilient and supportive infrastructure, promotion of sustainable and inclusive industrialization and support system for fostering innovation is the cornerstone of the Goal 9.

Goal 10 Reduced Inequalities

• Inequality is, and it will be a big problem for the world, both on the international and national levels.

Goal 11 Sustainable Cities and Communities

• Adapting and creating more inclusive and safer cities and settlements and improving their resilience and sustainability is the foundation of Goal 11.

Goal 12 Responsible Consumption and Production

• Enabling and establishing the system for improving sustainability in production and consumption is the basis for Goal 12.

Goal 13 Climate Action

• The urgency to deal with climate change and its impacts are rising daily.

Goal 14 Life Below Water

• Oceans, seas, and marine resources were highly disregarded in terms of their preservation. Through Goal 14 UN is aiming to improve its sustainability.

Goal 15 Life on Land

• Stopping the negative impact of human actions on the terrestrial ecosystems, reversing the process of deforestation, and halting biodiversity loss are the primary elements of the Goal 15 actions.

Goal 16 Peace, Justice and Strong Institutions

• Establishment and insurance of the competent, accountable, and inclusive institutions at all levels, promotion of peace and inclusive societies, and extending the access to justice for all are the main concerns for Goal 16.

Goal 17 Partnership for the Goals

• Improving the process and means for implementation of the Sustainability Agenda and revitalization of the global partnership, and higher participation in the realization of the SDG are essential segments for Goal 17.

The Sustainable Development Goals Report 2018 reviews progress in the third year of implementation of the 2030 Agenda for Sustainable Development (United Nations, 2018).

Goal 1: Only 45 per cent of the world's population are covered by at least one social protection cash benefit.

Goal 2: World hunger is on the rise again, wasting and overweight still affected millions of children under age 5.

Goal 3: Births attended by skilled health personnel increased globally.

Goal 4: More than half of children and adolescents are not achieving minimum proficiency in reading and mathematics.

Goal 5: Women spend about three times as many hours in unpaid domestic and care work as men.

Goal 6: 3 in 10 people lack access to safely managed drinking water service, 6 in 10 people lack access to safely managed sanitation facilities.

Goal 7: 4 in 10 people still lack access to clean cooking fuels and technologies.

Goal 8: Earning inequalities are still pervasive: men earned 12.5 per cent more than women, youth were three times more likely to be unemployed than adults.

Goal 9: Global carbon intensity decreased by 19 per cent between 2000 and 2015.

Goal 10: Remittances to low- and middle-income countries represented over 75 per cent of total global remittances.

Goal 11: Damage to housing due to natural disasters showed a statistically significant rise.

Goal 12: Globally by 2018, 108 countries had national policies on sustainable consumption and production, 93 per cent of the world's 250 largest companies are now reporting on sustainability.

Goal 13: The majority of countries have ratified the Paris Agreement and provided nationally determined contributions.

Goal 14: Open ocean sites show current levels of acidity have increased by 26 per cent since the start of the Industrial Revolution.

Goal 15: Land degradation threatens the security and development of all countries, The Red List Index shows alarming trend in biodiversity decline for mammals, birds, amphibians, corals and cycads.

Goal 16: The proportion of prisoners held in detention without being sentenced for a crime remained almost constant in the last decade: from 32 per cent in 2003–2005 to 31 per cent in 2014–2016.

Goal 17: Securing a strong and well-resourced under the next MFF ultimately depends on the role and place of development policy vis-à-vis other EU policies.

The report also shows that progress is insufficient to meet the Agenda's goals and targets by 2030. This is especially true for the most disadvantaged and marginalized groups. Some forms of discrimination against women and girls are declining gender inequality continues to hold women back and deprives them of basic rights and opportunities.

4. GOALS OF SUSTAINABLE ECONOMIC DEVELOPMENT IN THE REPUBLIC OF SERBIA

Sustainable economic development is an integral part of the macroeconomic policy of modern economies. Building an effective institutional framework at all levels is the basis for achieving the Sustainable Development Goals. Institutional mechanisms for implementing sustainable economic development are reflected in the definition of Strategies that contain key principles and goals of sustainable economic development, as well as, measures and mechanisms for its implementation. The implementation of the Strategies is handled by the competent ministries as well as by the Office for Sustainable Development.

Excessive institutional and procedural frameworks, can adversely affect the implementation of the concept, as well as, the lack of interest of all parties. Many countries have been creative in the formation of new institutions, but the barriers that have emerged have diminished their effectiveness, so that the necessary strategic participation requires the active participation of high-level key ministries and strong political support. Ministries do not always have a complete or identical understanding of the sustainable development process, and it is the responsibility of the Sustainable Development Office to address all issues in a comprehensive manner. It is also important that the costs/benefits to society of implementing sustainable development are clearly expressed and that citizens are informed about it. In addition, it is necessary to build a modern and efficient public administration as a system of institutions that jointly lead to sustainable development while improving cooperation and coordination between the sector, as well as, the public administration and the private and civil sectors.

In addition to developing Sustainable Development Strategies, national economies also develop an action plan for implementing the Strategy. The National Sustainable Development Action Plan is a key mechanism for the implementation of the Strategy as it develops the objectives set out in the Strategy into activities. Sustainable development indicators are defined internationally for monitoring the measures taken. The choice of indicators reflects a link to the key proposed instruments. The selected indicators are in line with the revised list of UN Sustainable Development Indicators, which also includes indicators of the implementation of the Millennium Development Goals. All indicators are gender-supported.

Achieving sustainable development in the Republic of Serbia is related to the introduction and application of EU-dominant principles, as well as, to enhancing competitiveness based on knowledge, innovation and entrepreneurship based on the principles contained in the Sustainable Development Declaration, the Millennium Development Goals and the EU Sustainable Development Strategy. Based on the above guidelines, the Sustainable Development Goals of the Republic of Serbia (RS Sustainable Economic Development Strategy) have been defined:

1) Intergenerational solidarity and intra - generation solidarity
2) Open and democratic society - citizen participation in decision making
3) Knowledge as a carrier of development
4) Involvement in social processes
5) Integration of environmental issues into other sector policies
6) Precaution
7) The polluter/user pays and
8) Sustainable production and consumption.

Principles 6, 7 and 8 are directly related to environmental protection and sustainable economic development. Thus, the precautionary principle requires maintaining a natural balance when there is no reliable information on a particular problem. Each activity must be planned and implemented in such a way as to cause the least possible change in the environment and preventive action must be taken to prevent possible negative impacts on the environment, especially if the welfare of humans and animals is threatened. Principle 7 relates to the incorporation of environmental costs into the price of a product (internalize environmental costs). Principle 8 is about respecting balanced relationships in the exploitation of natural resources and ensuring a high level of protection and improvement of the quality of the environment. The principle also relates to environmental pollution and the promotion of sustainable consumption and production, as well as, economic growth, which must not cause a proportional increase in environmental degradation.

Sustainable economic development is one of Serbia's key national priorities. Key national priorities have been defined with the aim of achieving a vision for sustainable development by 2017 (Sustainable Economic Development Strategy). They cover the following priorities:

• EU membership

The Republic of Serbia has to fulfill numerous obligations and conditions, among which the harmonization with the procedures and taking over the obligations arising from that membership take an important place.

• Developing a competitive market economy and balanced economic growth, fostering innovation, creating better links between science, technology and entrepreneurship, increasing R&D capacity.

In order to achieve this priority, conditions for attracting foreign direct investment and macroeconomic stability need to be improved. In addition, it is necessary to encourage innovation and promote entrepreneurship, as well as promote the information society.

•Developing and educating people, increasing employment and social inclusion, creating more jobs, attracting professionals, improving the quality and adaptability of the workforce, increasing investment in human resources.

Achieving this priority requires the creation of better working conditions that will prevent the outflow of experts, as well as, investing in people's knowledge and skills through quality, effective and practically applicable education and continuous improvement of equal opportunities for members of all social groups. In addition, it is necessary to achieve greater social inclusion of young people, women and members of marginalized groups and to invest in public health, especially in primary health care and prevention.

• Infrastructure development and balanced regional development, improving the attractiveness of the country and ensuring adequate quality and level of services.

Achieving this priority requires the expansion and improvement of transport infrastructure, the development of communal infrastructure and the reduction of regional inequalities and poverty. It is also important to raise regional competitiveness and foster even regional development.

• Protection and improvement of the environment and rational use of natural resources, conservation and improvement of the environmental protection system, reduction of pollution and environmental pressures, use of natural resources so that they remain available for future generations.

In order to achieve this priority, it is necessary to establish a system of protection and sustainable use of natural resources, (air, water, land, minerals, forests, fish, wild flora and fauna) and the inclusion of environmental policies in the development policies of other sectors. In addition, the importance of investing in reducing environmental pollution and developing cleaner technologies, encouraging the use of renewable energy sources, protecting and conserving biodiversity is also emphasized.

The strategic framework of the Republic of Serbia is dedicated to achieving the goals of sustainable development. Serbia is also making additional efforts to harmonize regulations in the EU accession process. The Sustainable Development Goals are divided into four groups:

- economic growth (Sustainable Development Goals 8 and 9)
- development of human resources (Sustainable Development Goals 1,2,3,4,5 and 10)
- environment and climate (Sustainable Development Goals 6,7,11,12,13 and 15) and
-institutions, finance and cooperation (Sustainable Development Goals 16 and 17).

Table 2. Milleniums goals and sustainable development goals in Serbia

Sustainable development goals in Serbia	**Sustainable Development Goals**
Economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
	End poverty in all its forms everywhere End hunger, achieve food security

	and improved nutrition and promote sustainable agriculture
Development of human resources	Ensure healthy lives and promote well-being for all at all ages Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all Achieve gender equality and empower all women and girls Reduce inequality within and among countries
Environment and climate	Ensure availability and sustainable management of water and sanitation for all Ensure access to affordable, reliable, sustainable and modern energy for all Make cities and human settlements inclusive, safe, resilient and sustainable Ensure sustainable consumption and production patterns Take urgent action to combat climate change and its impacts Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Institutions, finance and cooperation	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

4.1. Sustainable development goals and 4.0 revolution

In 2020, they are defined the 11 emerging priorities for countries to achieve economic transformation: moving towards a full integration of social, environmental and institutional targets into their economic systems (The Global Competitiveness Report Special Edition 2020: How Countries are Performing on the Road to Recovery, 2020):

1. Ensure public institutions embed strong governance principles and a long-term vision and build trust by serving their citizens

The preparedness of countries on this priority area is measured here using metrics on judicial independence, corruption perception, digital media trustworthiness and a composite index reflecting the ability of citizens to exercise formal rights and liberties.

2. Upgrade infrastructure to accelerate the energy transition and broaden access to electricity and ICT

The transition to a greener and more inclusive economy will have to be underpinned by significant investments in infrastructure, including an expansion of digital networks. Infrastructure upgrades should comprise the expansion of digital capacity to match the benefit of digitalization with universal access to opportunities.

3. Shift to more progressive taxation, rethinking how corporations, wealth and labor are taxed, nationally and in an international cooperative framework

The assessment of countries' readiness is based on an aggregate measures of the progressivity of personal, corporate and value added tax; an inheritance tax indicator; a tax productivity indicator (taxes collected relative to the tax base) and a metric that measures the impact of taxation on inequality.

4. Update education curricula and expand investment in the skills needed for the jobs and "markets of tomorrow"

The education systems should be upgraded to provide digital skills and critical thinking skills through schools and universities, as well as, ongoing learning and skilling through public and private life-long learning programs.

5. Rethink labor laws and social protection for the new economy and the new needs of the workforce

Examples of these protections include social protection coverage, guaranteed minimum income benefits, accessibility of healthcare services, inequality adjusted access to education, expenditure for housing allowances, active labor market policies, enforcement of minimum wage, adequate overtime regulation, workers' rights, impact of the online gig economy on working conditions, and employment opportunities for the low-skilled.

6. Expand eldercare, childcare and healthcare infrastructure, access and innovation for the benefit of people and the economy

Examples of these protections include social protection coverage, guaranteed minimum income benefits, accessibility of healthcare services, inequality adjusted access to education, expenditure for housing allowances, active labor market policies, enforcement of minimum wage, adequate overtime regulation, workers' rights, impact of the online gig economy on working conditions, and employment opportunities for the low-skilled.

7. Increase incentives to direct financial resources towards long-term investments, strengthen stability and expand inclusion

More effective and stringent measures on rewards to executives, dividends, share buybacks, cash holdings and financial investments by non-financial corporations could also help channel resources towards the investments needed to increase productivity, protect people and the environment, and avoid practices that aim for short-term increases in market valuation.

8. Rethink competition and anti-trust frameworks needed in the Fourth Industrial Revolution, ensuring market access, both locally and internationally

The data points included to assess countries readiness in this area consist of effective taxation for new economy, transnational firms; the extent of market dominance; the growth of innovative companies; financing of SMEs; venture capital availability, as well as, proxies of local opportunities (state of cluster development, ratio of unemployment between rural and urban population).

9. Facilitate the creation of "markets of tomorrow", especially in areas that require public-private collaboration

To measure countries' readiness on these aspects, available data include trade-adjusted emission levels to provide a measure of overall sustainability of consumption patterns within the country, as well as buyer sophistication, the role of the public sector in fostering demand for new technologies, consumer uptake of new technologies, pledges relative to overall patenting activity, and perception within the business community of the adequacy of existing regulation of emerging technologies.

10. Incentivize and expand patient investments in research, innovation and invention that can create new "markets of tomorrow"

To measure these aspects would require data on aspects such as investments in long-term science and research projects, availability of patient capital for targeted development of new technologies, governments' capacity to act as a de facto venture capitalist, time-horizon of research and the amount of development spending across countries.

11. Incentivize firms to embrace diversity, equity and inclusion to enhance creativity.

Progress of countries on promoting diversity, equity and inclusion in their workforce has been measured by the gender diversity of the workforce, the propensity of companies to rely on professional management rather than friends and the presence of women in tech roles and in ownership structures.

The analysis of these priorities shows that priority two refers to sustainable development and that priority eight refers to the 4.0 revolution.

4.2. Sustainable development and DESI

Economic policy under conditions of competitive relations at the global and regional level assumes a knowledge-based economy. Knowledge economy implies a positive and stimulating influence on the whole network of economic and development factors. The knowledge economy model is based on information and knowledge that is shared and shared. The very application of the knowledge-based economy model presupposes certain structural macroeconomic changes and the construction of a system of sustainable production and consumption. The concept is based on the production of as much additional value as possible, with the lowest consumption of materials and energy and with the least negative environmental impact (waste management, reduction of harmful emissions, green packaging, recycling of existing by-products). Today's globally applicable product lifecycle concept refers to sustainable production and consumption that includes environmental, material and energy efficiency at every stage of production of goods and services. At every moment of the product's existence, its manufacturers, distributors and consumers must be aware of and accountable for all its environmental, socio-cultural and other consequences.

Perspectives of sustainable development of the macroeconomic environment in the Republic of Serbia can be viewed using the model of small open economy, which should build its position and competitiveness by accepting theoretical postulates of macroeconomics and experience of successful small knowledge-based economies. These are countries with up to 10 million inhabitants and a national income of about $ 5,000 per capita, exporting at least 50% of GDP and where knowledge is a key resource. To achieve sustainable growth based on the knowledge economy, better economic growth and qualitative development effects: technological progress, structural change, productive employment and increased competition. Measures to achieve this goal should be oriented towards stimulating domestic and foreign investment, accelerating privatization and restructuring the public sector in a consistent and socially responsible way,

The basic prerequisite for increasing employment and reducing unemployment is the growth of the economy, especially in the services sector, but based on the application of knowledge and new technology, i.e. an economy that is competitive in international contexts.

The development of the digital economy as part of the knowledge economy is driven by technological innovation, the emergence of new products and services, changing needs and demands of clients, as well as, changes in the education, habits and lifestyle of the population.

The application of new technologies has enabled the development of new products and services, as well as, changes in the volume and structure of demand in the market of products and services. New technologies have led to multiple benefits in terms of reducing business costs, enhancing customer awareness of products and services, innovating in business, and offering standard and non-standard products. Given the importance of developing the digital economy and monitoring development, it is calculated the Digital Economy and Society Index (DESI). DESI is a complex index that summarizes relevant digital performance indicators and tracks the development of EU countries in digital competitiveness (DESI, 2020).

DESI has been calculated for EU countries since 2014, while for Serbia it is calculated for the first time in 2017, which enables Serbia to be positioned on the European digital performance map. The index for Serbia is calculated according to the May 2018 methodology of the European Commission. The most advanced digital economies in the European Union in 2018 are Finland, Sweden and the Netherlands, with Bulgaria, Romania and Greece at the top. Serbia has ranks 25th in the list of European countries, up from 28th last year. This result still places Serbia in a cluster of relatively low-performing countries, comprising Romania, Greece, Bulgaria, Italy, Poland, Hungary, Croatia, Cyprus and Slovakia (Ratel, 2019).

5. CONCLUSION

In modern economies, all considerations of economic development are in the context of sustainable development. The Sustainable Development Goals are a complex category whose achievement should contribute to a better quality of life for all citizens and social well-being. The 2030 Agenda and the Sustainable Development Goals are of great importance as they represent practical guidelines that should be pursued by macro-economies. Sustainable economic development is realized in the conditions of the fourth industrial revolution. The paper points out that the context of sustainable development includes the fourth industrial revolution in terms of goals and priorities. In addition, the development of this revolution will foster the competitiveness and innovation of national economies.

REFERENCES

[34] Zhou, K., Liu, T., & Zhou, L.: Industry 4.0: Towards future industrial opportunities and challenges. In 2015 *12th International Conference on fuzzy systems and knowledge discovery (FSKD)* (pp. 2147-2152). IEEE. Zhangjiajie, China, 2015

[35] Stock, T., Seliger, G.: Opportunities of sustainable manufacturing in industry 4.0. *Procedia Cirp*, 40, pp. 536-541, 2016

[36] Lopez de Sousa Jabbour, A. B. L., Jabbour, C. J. C., Foropon, C., Godinho Filho, M.: When titans meet - Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. *Technological Forecasting and Social Change*, 132, pp. 18-25, 2018

[37] https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2019.pdf, 2019, The Global Competitiveness Report, Accessed on: 2022-04-03

[38] https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2021.pdf, 2021, WIPO, Global Innovation Index 2021: Tracking Innovation through the COVID-19 Crisis. Geneva: World Intellectual Property Organization. Accessed on: 2022-01-03

[39] Pearce, D. W., Markandya, A., Barbier, E.: *Blueprint for a Green Economy*. London, Earthscan, 1989

[40] https://www.are.admin.ch/are/en/home/sustainable-development/international-cooperation/2030agenda/un-_-milestones-in-sustainable-development/1987--brundtland-report.html, 1987, World Commission on Environment and Development, *Our common future. Brundtland Report*. Accessed on: 2022-02-08

[41] https://www.un.org/en/development/devagenda/millennium.shtml, 2000, The United Nations Millennium Declaration, Accessed on: 2022-02-19

[42] https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf, United Nations, 2015, United Nations: *Transforming our world: The 2030 Agenda for sustainable development*, Accessed on: 2022-03-19

[43] https://unstats.un.org/sdgs/files/report/2018/TheSustainableDevelopmentGoalsReport201 8-EN.pdf, 2018, United Nations: *The Sustainable Development Goals Report 2018*, Accessed on: 2022-02-03

[44] http://www.zurbnis.rs/zakoni/Nacionalna%20strategija%20odrzivog%20razvoja.pdf, Nacionalna strategija održivog privrednog razvoja. Accessed on: 2022-01-03

[45] https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2020.pdf, 2020, The Global Competitiveness Report Special Edition 2020: How Countries are Performing on the Road to Recovery, Accessed on: 2022-01-18

[46] http://benchmark.ratel.rs/pregled-rezultata-cyr-2019, 2019, Ratel, Pregled rezultata, Accessed on: 2022-01-27

[47] https://eufordigital.eu/library/digital-economy-and-society-index-desi-2020/, 2020, DESI Index, Accessed on: 2022-01-23

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COMPARISON OF THE SIZE AND EFFICIENCY OF A TWO-CARRIER PLANETARY GEAR TRAIN AND KINEMATICALLY EQUIVALENT PLANETARY GEAR TRAINS

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Abstract: *A two-carrier planetary gear train (PGT) developed for a specific purpose is discussed in this paper. This PGT is suitable for applications which require negative transmission ratios in the range from -3 up to -143. The mechanical and dimensional characteristics of the planetary gear train for nominal negative transmission ratios of -30 and -40 have been considered. Many combinations of ideal torque ratios of the PGT were obtained for the mentioned transmission ratios, from which only the combinations providing the minimum radial dimensions of the planetary gear units were selected. It was found that the minimum radial dimensions of the PGT will be obtained when the ratio of the reference diameters of the planetary unit ring gears of is close to unity, i.e., when the PGT housing is cylindrical rather than stepped. An introduction to single speed two-carrier planetary gear trains is given, in addition to an overview of the application of the DVOBRZ software package used to synthesize different gearboxes for the required transmission ratio. Acceptable gearboxes were selected from all PGTs according to the criteria of minimum dimensions and acceptable efficiency, and their construction concepts were created.*

Keywords: *Two-Carrier planetary gear train; transmission ratio;efficiency*

1. INTRODUCTION

All machines require some form of mechanical power transmission, as it enables the transfer of mechanical energy from the driving machine to the driven machine. Besides that, the transmission provides other useful functions, such as changing the direction, frequency or magnitude of forces or torques acting on the driven machine [1].
Geared transmissions are some of the most used forms of power transmission, and planetary gear trains (PGTs) are a special variant of geared transmission which offers several advantages in relation to conventional gear trains. The most notable advantage is a compact design and improved durability and reliability due to the beneficial effect of power being split over several planet gears, which may be even further enhanced by vibration analysis and customized bearing solutions [2]. This has enabled the design of PGTs having high power ratings combined with a wide range of transmission ratios. However, a large diversity of kinematic schemes and the need for relatively complex calculations in comparison to conventional gearboxes, means that systematic research must be undertaken to realize the full potential of planetary gearboxes.
Current research shows that industrial applications use transmission with ratios in the range from 18 to 90 [3]. A basic type of PGT designated as 1AI is usually used for transmission ratios in the range from 3 to 8 and may be exceptionally used up to 12. This means that compound PGTs, created by combining two PGTs of basic type must be used to achieve the required transmission ratios [4,5,6,7,8].
Gearboxes using such compound PGTs have found a range of applications in cranes and transportation technology in general. Machine tool gearboxes are also an important area of application and optimization of two-carrier two-speed PGTs with brakes on coupled shafts which was covered in [9]. The possibility of optimization of two-carrier two-speed PGTs with brakes on single shafts for fishing boat main propulsion gearboxes is covered in [10].
Planetary gear trains have been widely used in the aviation industry, due to their small size and weight, quiet, smooth running, high loading capacity and long service life. A method for predicting the reliability of planetary gear train in partial load state was presented in [11].
The application of PGTs in the automobile and automation industries is also important, notably in

automatic transmissions containing any number of simple, compound or complex-compound planetary gear sets [12]. New concepts for the calculation of internal power flows such as the split-power ratio and the virtual split-power ratio have been introduced and presented in [13].
PGTs are also used in electric vehicles because of their high power density and ability to be designed and operated as a multi speed transmission. A hybrid dynamic model for helical PGTs that operate in conditions of high and variable input speed was proposed in [14].
There has been relatively little research into two-carrier PGTs, mostly sporadic, however some systematic research into multi-carrier PGTs has been carried out in the last decade or so. The structures or means of connection between the component gear trains have been systematically researched in [15] and methodology has been provided to determine the transmission ratios and efficiency by means of lever analogy.
The kinematic properties of the structures have been extensively researched in [16,17] as well as the efficiencies of single and two-speed PGTs by means of the torque method from [18,19].
Furthermore, within the research carried out in [3] the DVOBRZ software was developed, enabling the synthesis, analysis, and optimal selection of two-carrier PGTs. Some of the results obtained by means of this software package have been used in this paper. The mechanical and dimensional characteristics of the planetary gear train for nominal negative transmission ratios of -30 and -40 have been considered. Several combinations of ideal torque ratios of the PGT were obtained, from which the combinations providing the minimum radial dimensions of the planetary gear units were selected. The best gearboxes were selected according to the criteria of minimum dimensions and acceptable efficiency, and their construction concepts were created.

2. THE RESEARCHED TWO-CARRIER, SINGLE SPEED PLANETARY GEAR TRAIN

The subject of this paper is a single speed two-carrier PGT. The application constraints require a kinematically negative transmission ratio of -30 and -40, with the component PGTs being of similar size. This will result in the casing having the simplest possible shape, which will in turn reduce manufacturing costs.
This type of casing can be achieved if the relation of maximum and minimal values of the ring gear diameters is close to one, and it is for this reason that the relation with ring gear diameters is considered.
Both component gear trains are the most commonly used simple PGT, 1AI, which is shown in Fig. 1 together with the specific torques on its shafts and its Wolf-Arnaudov symbol [7]. It is of relatively simple construction, its parts being the sun gear 1, the planet gears 2, the ring gear (annulus) 3 and planet carrier S.
The Wolf-Arnaudov symbol simplifies the representation of PGTs as the train shafts are represented by lines of different thickness and a circle. The sun gear shaft 1 is represented by a thin line, the ring gear shaft 3 by a thick line and the carrier shaft *S* by two parallel lines. The carrier shaft is the summary element because a negative transmission ratio is obtained by locking the planet carrier.

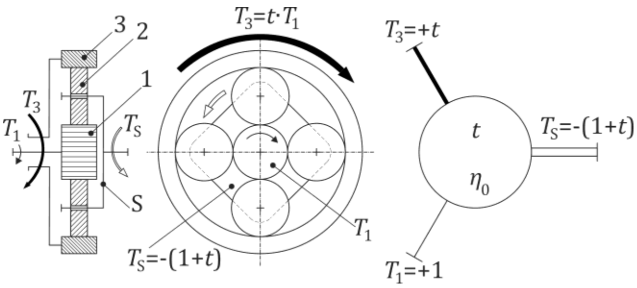


Fig.1. 1AI, the most used simple PGT with the specific torques on its shafts and its Wolf-Arnaudov symbol

It should be noted that the ideal torque ratio t of the PGT is given by Eq. (1), while the shaft torque ratio is given by Eq. (2), where z_1 is the number of teeth of the sun gear, z_3 is the number of teeth of the ring gear, T_1 is the torque acting on the sun gear shaft, T_3 is the torque acting on the ring gear shaft, T_S is the torque acting on the planet carrier shaft, and T_D is the differential torque:

$$t = \frac{T_3}{T_1} = \frac{T_{D\max}}{T_{D\min}} = \frac{|z_3|}{z_1} > +1 \tag{1}$$

$$T_1 : T_3 : T_S = +1 : +t : -(1+t) \tag{2}$$

Multi-carrier PGTs are created by connecting the shafts of simple PGTs (1AI) [6]. As two-carrier PGTs are the subject of this paper, we shall consider one-speed, two-carrier PGTs with three external shafts composed of two simple basic PGTs. Two of the three external shafts are single shafts and the third one is a compound shaft, as indicated in Fig. 2.

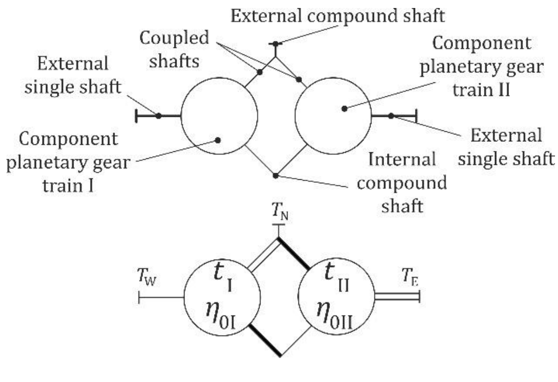
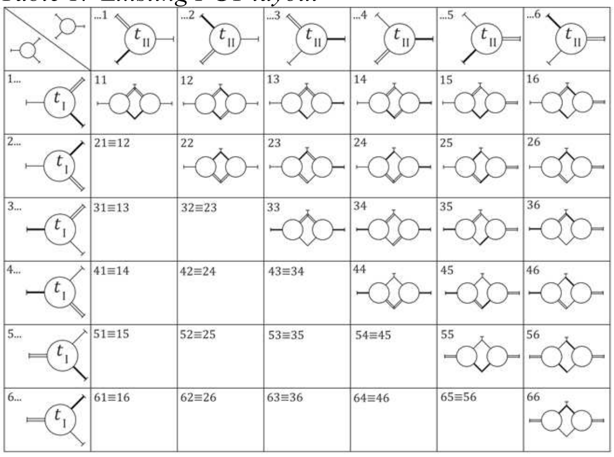


Fig.2. Two-carrier PGT symbol with shafts and respective torques marked

The torque markings of the external shaft torques (T_W, T_N and T_E) follow the cardinal directions (W, N, E), and are ordered from power input to power output. The symbol contains the markings of the ideal torque ratio (t_I and t_{II}) and efficiency (η_{0I} and η_{0II}) for every basic component PGT [10].
An overview of possible structures of two-carrier single speed PGTs has been given in Table 1 [7]. It shows that

the simple component PGTs can be combined in 36 possible ways, giving 36 different PGT symbols. As some layouts are isomorphous, this is reduced to 21 practical layouts. Every PGT can provide six different operating modes, as the stationary member may be any of three external shafts, with the remaining two external shafts acting as input and output.

Table 1. Existing PGT layout



Therefore, it is possible to achieve a total of 126 different transmission variants [7]. The scheme and operating mode are noted with a matrix type designation (e. g. S15 – line 1, column 5), while the power input and output are marked by cardinal directions, the stationary element being placed in parentheses. Therefore, S15WN(E) points to layout 15 with power input being in the west, power output being in the north, and the eastern shaft being locked. However, as we explicitly state that the PGT has three external shafts, it is enough to write just S15WN to fully designate a PGT.

3. DVOBRZ SOFTWARE PACKAGE

Since the DVOBRZ software was used to identify variable solutions under application constraints, the principle of operation of the software is explained in detail in [20] and will be briefly presented in this paper. The DVOBRZ program was originally developed to identify the variants of two-carrier PGTs and their parameters that fulfil the kinematic requirements, and list them in order of priority according to the selection criterion, e.g., maximal efficiency, minimal weight, or size. The program can provide solutions for two-speed and single-speed gearboxes, depending on whether the actual gearbox will have a fixed transmission ratio or a user operated shifting mechanism.
The program operates by checking the ideal torque ratios of every possible combination of simple component gear trains and discards those that cannot provide the required transmission ratios. The transmission ratio for both gears is calculated for every possible combination of ideal torque ratios and is checked whether it is within the tolerance range for the desired transmission ratios. The ideal torque ratios are represented using the numbers of teeth on sun and ring gears for both component gear trains (Eq. 3 and Eq. 4):

$$t_{\mathrm{I}} = \frac{|z_{3\mathrm{I}}|}{z_{1\mathrm{I}}} \tag{3}$$

$$t_{\mathrm{II}} = \frac{|z_{3\mathrm{II}}|}{z_{1\mathrm{II}}} \tag{4}$$

The tooth numbers of the sun gears $z_{1\mathrm{I}}$ and $z_{1\mathrm{II}}$ must be set on program initialization. The program will then enlarge one ring gear (usually $z_{3\mathrm{I}}$) by one tooth and check whether the ideal torque ratio is valid, which is achieved if the simple component gear train satisfies the assembly conditions. If it does not, the ideal torque ratio is discarded, and the ring gear enlarged by one more tooth. This procedure is repeated until a valid ideal torque ratio is found or the maximum allowable ideal torque ratio for that component gear train is reached. The same procedure will then be carried out for the second simple component gear train.
The program calculates and stores the values of different parameters for each valid member of the set of ratios (basic geometry of component gear trains, component efficiency, transmission ratios, overall efficiency for each transmission ratio etc.) as a function of the ideal torque ratios of the component gear trains t_{I} and t_{II}. The resulting database is then used to select the best gearbox variant for the application, whether according to a single criterion (overall efficiency, minimal ratio of ring gear reference diameters, reference diameter of the largest ring gear etc.), or by multi-criteria optimization. In the case of multi-criteria optimization, the weighting coefficients for each optimization criteria must be determined according to the application conditions, depending on how important each criterion is for the application demand.
However, a kinematic scheme must be created for any selected layout variant to check out whether the solution is kinematically valid, and that it meets the relevant design and technological criteria.

3.1. Application of the DVOBRZ Software Package

Example 1
The DVOBRZ software package was used to determine the basic parameters of transmissions fulfilling the application demands. The most important input data is summarized as follows:

- Overall transmission ratio i=-30,
- Number of teeth of the first sun gear $z_{1\mathrm{I}}$ = 21(selected value),
- Number of teeth of the second sun gear $z_{1\mathrm{II}}$ = 21 (selected value),
- Number of planets per PGT k = 3 (application demand),
- Gear material 16MnCr4 steel (application demand),
- Average value of planet bearing losses coefficient k_{b} = 0,065 [3,5],
- Average value of seal frictional losses coefficient k_{s} = 0,05 [3,5],
- Average value of churning losses coefficient k_{c} = 0,125 [3,5],
- Gear width to diameter ratio b / d_1 = 0,7 (selected value),
- Efficiency $\eta \geq 0{,}93$ (application demand).

The design parameters required to manufacture the PGT were determined from constraints suggested in the literature, although it is expected that all gears will be made from the same material.
The analysis module finds 16 variants of transmissions which require demands, however due to isomorphy there are only 10 different variants. The schematic review of these variants is shown in Fig. 3.

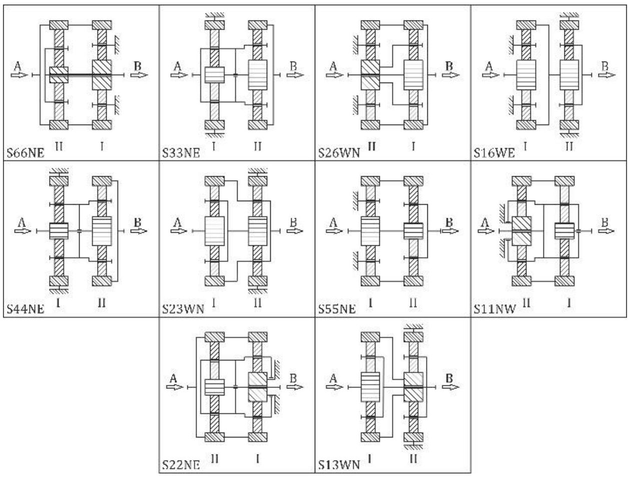


Fig.3. Single speed transmission variants

Analysis of the program results shows that the optimal solution in accordance with the criteria of maximum efficiency provides a borderline increase in efficiency in relation to the solution for minimal dimensions, however the component PGTs will have different outside diameters. Therefore, it can be concluded that the better solution is to optimise for equal outside diameters, as the decrease in overall efficiency will be negligible. The indicator of approximately equal outside diameters is the relation of maximal and minimal values of outside diameters of the two component gear trains which has to be close to unity.
The research results are condensed in Table 2 taking into consideration the following criteria: housing shape, efficiency and maximum transmission diameter.

Table 2. Research results in Example 1

Variant	t_I	t_{II}	d_{max}/d_{min}	d_{max}	η	m_I	m_{II}
S66NE	4	3,83	1,043	216	0,52	3	3
S55NE	3,17	3,67	1,081	231	0,77	3,75	3,5
S26WN	6,5	3	1,020	234	0,97	2	4,25
S16WE	6,83	3,33	1,025	246	0,97	2	4
S44NE	3,67	3,17	1,022	247,5	0,77	3,75	4,25
S23WE	7,33	3,5	1,014	267,7	0,97	2	4,25
S33NE	5,17	5	1,033	279	0,50	3	3
S13WN	7,83	3,83	1,022	282	0,97	2	4
S22NE	4	4,17	1,008	378	0,52	5,25	5
S11NW	5	4,83	1,017	435	0,50	4,75	5

The variant S13WN shown in Fig. 4 is chosen as the optimal transmission, even though it has internal power circulation. However, it is insignificant [21], and the internal power flow may be seen in Fig. 5. The reason for such a decision is the fact that this variant is easy for manufacturing and it has been already studied in literature [22].

This gear train layout is composed of component gear trains I and II. Input A is connected to sun gear I, while planet carriers I and II are connected to a common shaft leading to output B. Ring gear I is connected to hollow sun gear II, through which the shaft connecting planet carriers I and II is passing. A large rolling bearing supports the rotation of ring gear I, while ring gear II is locked to the gear train casing.

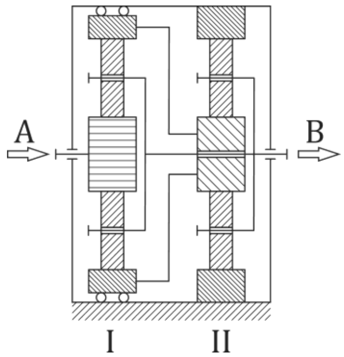


Fig.4. Schematic overview of the two-carrier, single speed planetary gear train S13WN

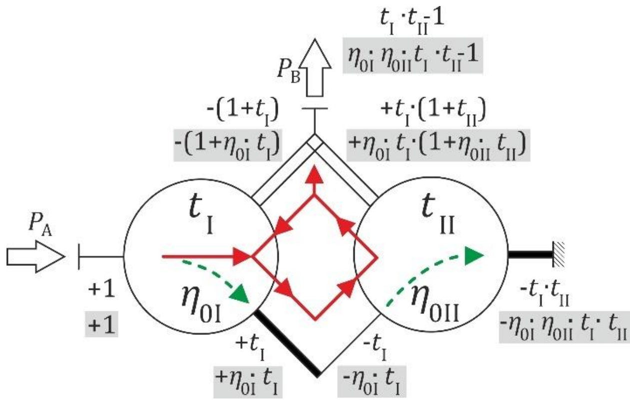


Fig.5. Torque method PGT analysis -ideal and real specific torques on all PGT shafts.

The analysis module finds possible solutions or combinations of ideal torque ratios for layout variants which provide the required transmission ratio. This data enables the creation of graphic representations of dependencies of different parameters.
The first graph is shown in Fig. 6. A considerable connection of values at x- and y-axes can be seen to exist. This makes sense since it is about maximum of ring gear diameter and relation of maximum and minimum of ring diameter: an increase at the y-axis implicates an increase at the x-axis, and the points (x, y) form a cloud in the x-y plane. The other dependencies from the analysis module are given in Figs. 7, 8 and 9.
Every point in the domain (horizontal x-y plane) presents a pair of ideal torque ratios enabling an overall torque ratio in the desired range. The vertical (z) axis on Fig. 7 presents the size ratio of the larger and smaller PGT ring gear diameters. The chart shows that this ratio can variate between 1 and more than 4. Further analysis of the results has shown that PGTs with z - axis values equal or close to one will have minimal radial dimensions.

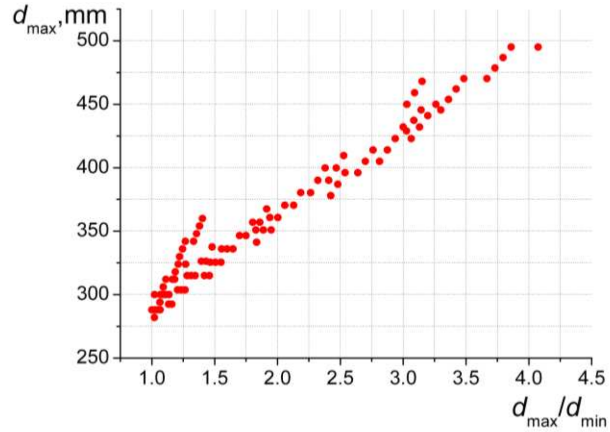


Fig.6. Correlation between maximal diameter of transmission and relation of ring gear reference diameters

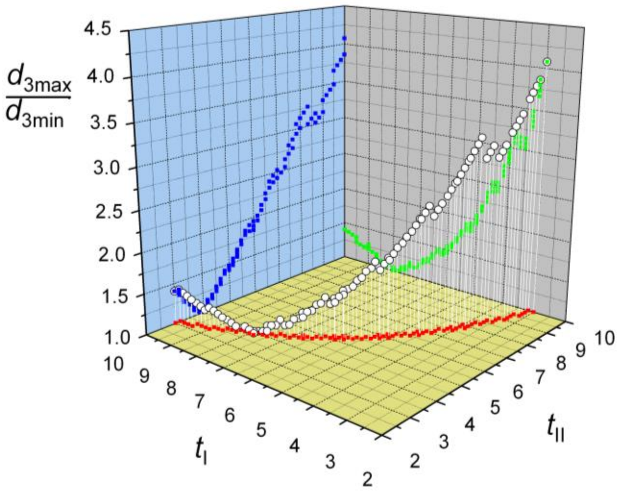


Fig.7. The influence of ideal torque ratios on the size ratio of of the larger and smaller ring gears diameters

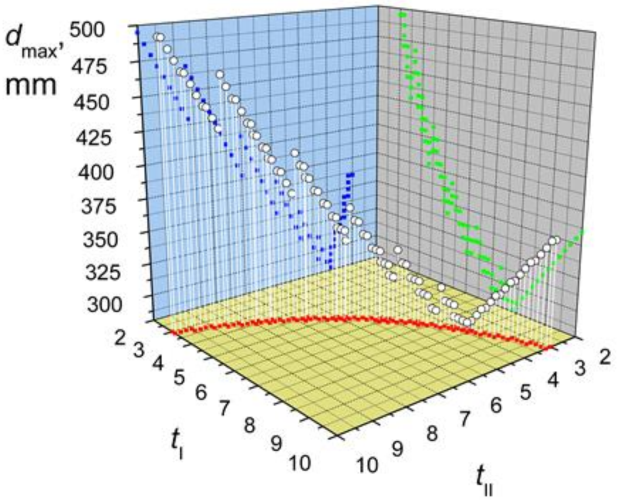


Fig.8. The influence of ideal torque ratios on maximal diameter of transmission in Example 1

Every point in the x-y plane of Fig. 8 also presents a pair of ideal torque ratios, while the z - axis presents the maximal diameter of the transmission.

The z – axis in Fig. 9 is used to represent the overall efficiency of the PGT in relation to the combination of ideal torque ratios. The chart shows that for torque ratios in the 2 to 10 range, efficiencies ranging from 0,944 to 0,969 can be achieved.

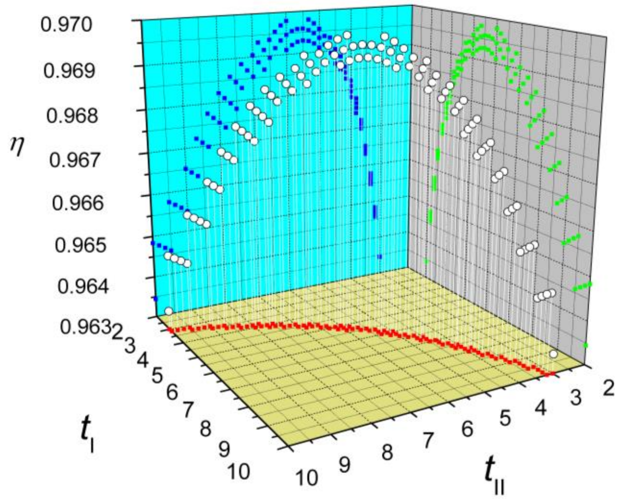


Fig.9. The influence of ideal torque ratios on overall efficiency

Example 2

In this example of application of the DVOBRZ software, only the overall transmission ratio is different, i = -40. The other input data is the same as in Example 1. The analysis module has also found 16 variants of transmissions which are in accordance with application demands. Due to isomorphy, there are only 10 different variants which is identical to Example 1.

The research results were processed in the same way as in Example 1 and are condensed in Table 3, taking into consideration all the criteria: housing shape, efficiency and maximum transmission diameter.

Table 3. Research results in Example 2

Variant	t_I	t_{II}	d_{max}/d_{min}	d_{max}	η	m_I	m_{II}
S26WN	7,67	3,67	1,016	280,5	0,97	2	4,25
S16WE	7,83	4	1,021	288	0,97	2	4
S66NE	5,83	5,67	1,03	288,7	0,49	2,75	2,75
S55NE	3,83	4,33	1,06	292,5	0,97	4	3,75
S44NE	4,33	3,83	1,064	312	0,76	4	4,25
S23WE	8,83	4	1,039	318	0,97	2	4,25
S13WN	8,67	4,67	1,077	336	0,50	2	4
S33NE	6,83	6,67	1,025	338,2	0,97	2,75	2,75
S22NE	5,67	5,83	1,029	551,2	0,52	5,25	5,25
S33NE	6,67	6,83	1,025	615	0,47	5	5

The variant S13WN was chosen in Example 2, for the same reasons as in Example 1.

There are 71 combinations of ideal torque ratios combination which satisfy the demands for *i* =-40, and they enable different dependencies between design parameters to be shown in Figs. 10, 11, 12, and 13.

First, the relation of the maximum transmission diameter and maximum to minimum ring gear diameter ratio is given in Fig. 10. The graph resembles Fig. 6, as the increase on y-axis implicates an increase on x-axis, and the points (x, y) form a cloud in the x-y plane. The difference is in the values at the x-axis and y-axis. The maximum value on the y-axis is higher than the value in Fig. 6, and the value at the x-axis is smaller than the value in Fig. 6.

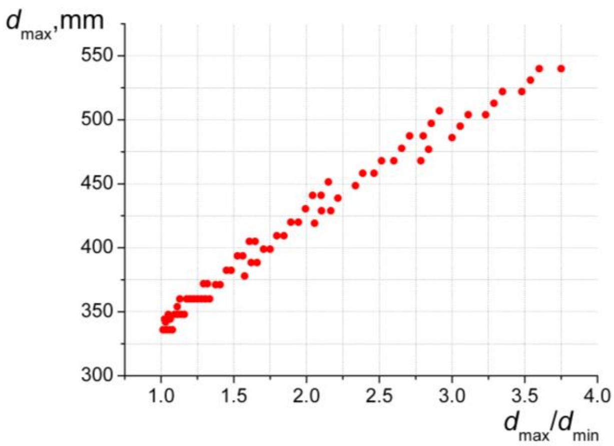


Fig.10. Correlation between maximal diameter of transmission and relation of ring gear reference diameters

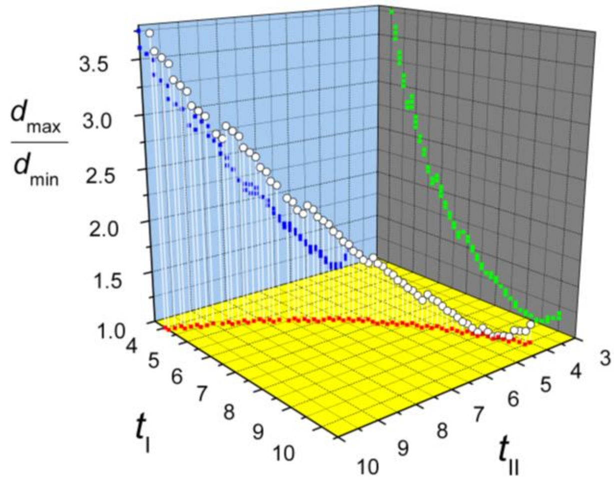


Fig.11. The influence of ideal torque ratios on the size ratio of of the larger and smaller ring gears diameters

Fig. 11 presents the size ratio of the larger and smaller PGT ring gear at the z-axis, while the horizontal x-y plane presents a pair of ideal torque ratios of the component gear trains. The chart shows that this ratio can variate between 1 and 4, and that the ideal torque ratios are in the range from 3 to 10.

Further analysis of the results has shown that PGTs with z - axis values equal or close to one will have minimal radial dimensions.

In Fig. 12, every point in the x-y plane presents a pair of ideal torque ratios (range from 3 to 10), while the z-axis presents the maximal diameter of transmission. The graph has a shape similar to the graph in Fig. 8, with slightly larger values at the z-axis.

Also, the ideal torque ratios are in relation with the overall efficiency of the PGT which is presented in Fig. 13. The z – axis in Fig. 13 is used to represent efficiency, while the x-axis and y-axis are used to represent the horizontal plane. The chart shows that for torque ratios in the 3 to 10 range, efficiencies ranging up to 0,972 can be achieved, which is a slightly larger value in comparision with the value in Example 1.

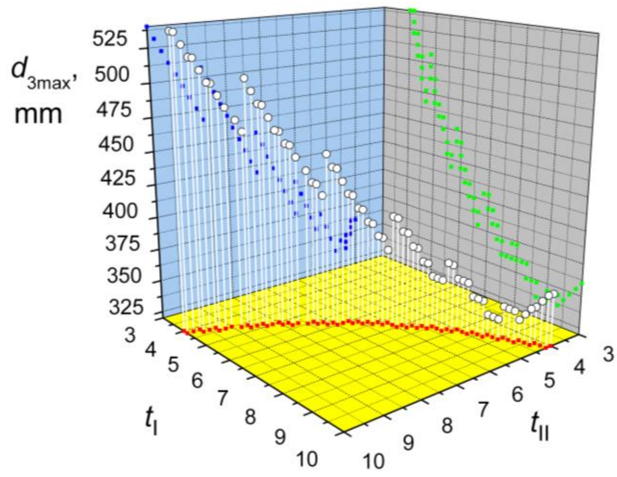


Fig.12. The influence of ideal torque ratios on maximal diameter of transmission in the example 2

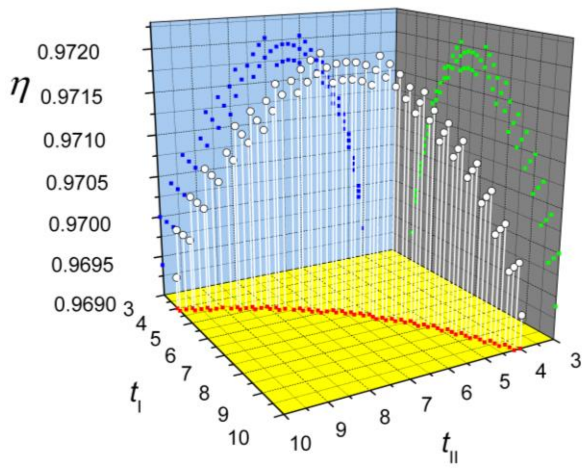


Fig.13. The influence of ideal torque ratios on overall efficiency

It is possible to determine the relation of the transmission efficiency to the overall transmission ratio, as visible in Fig. 14. It has been determined that the efficiency increases with the transmission ratio for this PGT type. Furthermore, it can be concluded from the diagram in Fig. 14 that PGTs with transmission ratios in the interval from -30 to -40 interval have very small variations in efficiency. The efficiency variations at transmission ratio of -40 are less pronounced than at transmission ratio of -30. This indicates that there is a very small window for PGT maximum efficiency optimization.

Also, there is a slight increase in maximal diameter of the transmission at transmission ratio of -40 in comparison to the maximal diameter of transmission at transmission ratio of -30. The curves change in the same way in the both examples.

Based on the analysis provided in the paper it can be concluded that more two variants provide necessary conditions, but detailed analyse is required. It is about variants S26WN and S16WE, shown in Fig. 15.

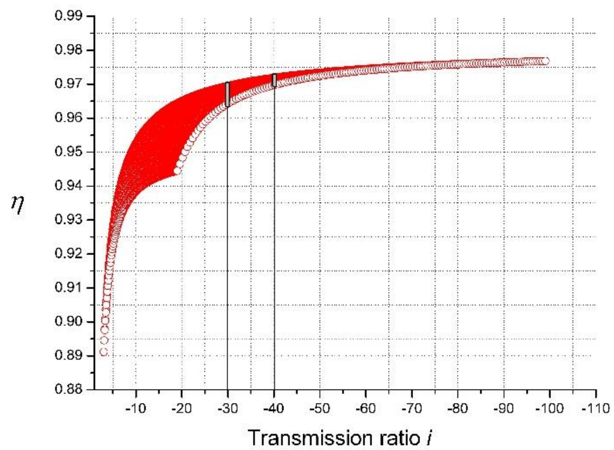


Fig.14. Influence of the overall transmission ratio on efficiency

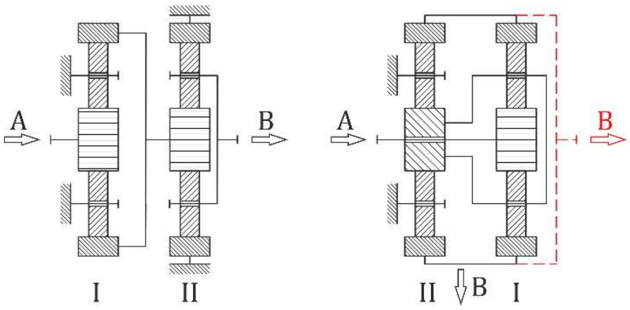


Fig.15. Schematic overview of the two-carrier, single speed planetary gear trains S16WE and S26WN (the original output located as in Fig. 3 has been added in dashed red lines for clarity)

Variant S16WE having the input and output shafts on opposite sides, while variant S26WN in an alternative configuration using the connecting outer ring gear shaft as the output. Variant S16WE is commonly used for marine propulsion and industrial applications, as the calculations for both component PGTs of S16WE are relatively simple and can be performed independently of each other. On the other hand, variant S26WN, in particular the alternate configuration described above, has recently found use as a replacement for elevator worm gear drives due to its high efficiency [23].

By comparing the parameters of variant S13WN and the other possible solutions, S26WN and S16WE it can be seen that solutions S26WN and S16WE have better values of maximal transmission diameters, while the efficiency remains in the same range of values. The relations of ring gear reference diameters are equal for the transmission ratio of -30, while solutions S26WN and S16WE have values closer to one for the transmission ratio of -40, providing a better solution than S13WN. However, S13WN remains the better solution if the selection criteria are limited to technological demands.

4. CONCLUSION

This paper deals with the analysis of a two-carrier PGT developed for a specific application, having a transmission ratio of -30 and -40. The application conditions request demand the type S13WN PGT to be used. The DVOBRZ software package was used to determine the variants and basic parameters of two-carrier drives within the application constraints, while taking into consideration the design parameters such as gear geometry of the component gear trains, overall transmission ratio, average value of internal losses, gear material and overall efficiency.

The values of different parameters for all valid PGTs were calculated and stored as a function of the ideal torque ratios of the component gear trains, and the resulting database was used to select the best gearbox variant for the application according to two criteria. The first criterion was minimization of the PGT dimensions, while the second was maximization of PGTefficiency.

Analysis has shown that the efficiency of a PGT optimised for minimum size will be borderline smaller than of a PGT optimised for maximum efficiency, but the PGT optimised for minimum size will be considerably easier to manufacture, due to both ring gears being of the same size.

Further analysis and comparison to all the other kinematically equivalent PGTs has shown that S13WN does not present the best solution according to either criterion. It has been determined that both S16WE and S26WN provide valid solutions according to both the criteria of minimum size and maximum efficiency. It must be also considered that those variants have no internal power circulation, resulting in a considerably lighter build in relation to S13WN. However, variant S13WN still retains precedence due to technological demands and the fact that this variant is thoroughly examined in literature.

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REFERENCES

[1] Jovanović, V., Janošević, D., Pavlović, J.: Analysis of the influence of the digging position on the loading of the axial bearing of slewing platform drive mechanisms in hydraulic excavators. *Facta Universitatis-Series Mechanical Engineering*, Vol. 19, No. 4, pp. 705-718, 2021, ISSN 0354-2025, 2021

[2] Liu, J., et al.: Influence of support stiffness on vibrations of a planet gear system considering ring with flexible support. *Journal of Central South University*, Vol. 27, No. 8, pp. 2280−2290, ISSN 2095-2899, 2020

[3] Karaivanov, D.: *Theoretical and experimental studies of the influence of the structure of coupled two-carrier planetary gear trains on its parameters*, Ph.D. Thesis, University of Chemical Technology and Metallurgy, Sofia, 2000.

[4] Kudrjyavtsev, V.N., Kirdyiashev, I.N.: *Planetary gear trains handbook*, Mashinostroenie, Leningrad, 1977.

[5] Looman, J.: *Zahnradgetriebe-Grundlagen, Konstruktion, Anwendung in Fahrzeugen*, 3. Aufgabe, Springer-Verlag, Berlin, ISBN 9783540894605,1996
[6] Mueller, H.W.: *Die Umlaufgetriebe-Auslegung und vielseitige Anwendungen*, 2. Aufgabe, Springer-Verlag, Berlin, ISBN 9783642587252, 1998
[7] Arnaudov, K., Karaivanov, D.P.: *Planetary gear trains*, CRC Press, Taylor & Francis Group, Boca Raton, FL, ISBN 9781138311855, 2019
[8] Troha, S., et al.: Coupled two-carrier planetary gearboxes for two-speed drives, *Machines, Technologies, Materials*, Vol. 15, No. 6, pp. 212-218, ISSN 1313-0226, 2021
[9] Troha, S., et al.: The selection of optimal reversible two-speed planetary gear trains for machine tool gearboxes, *Facta Universitatis-Series Mechanical Engineering*, Vol. 18, No. 1, pp. 121-134, ISSN 0354-2025, 2020
[10] Stefanović-Marinović, J., Troha, S., Milovančević, M.: An application of multicriteria optimization to the two-carrier two-speed planetary gear trains, *Facta Universitatis - Series Mechanical Engineering*, Vol. 15, No. 1, pp. 85-95, ISSN 0354-2025, 2017
[11] Ming, L., Liyang, X., Lijun, D.: Load sharing analysis and reliability prediction for planetary gear train of helicopter, *Mechanism and Machine Theory*, Vol. 115, pp. 97-113, ISSN 0094-114X, 2017
[12] Kahraman, A, et al.: A Kinematics and Power Flow Analysis Methodology for Automatic Transmission Planetary Gear Trains, *Journal of Mechanical Design*, Vol. 126, pp. 1071-1081, ISSN 1050-0472, 2004
[13] Chen, C.: Power flow and efficiency analysis of epicyclic gear transmission with split power, *Mechanism and Machine Theory*, Vol. 59, pp. 96-106, 2013
[14] Changhao, L., et al.: Hybrid dynamic modeling and analysis of the electric vehicle planetary gear system, *Mechanism and Machine Theory*, Vol. 150, Article no. 103860, ISSN 0094-114X, 2020
[15] Arnaudov, K., Karaivanov D., Engineering analysis of the coupled two-carrier planetary gearing through the lever analogy, *Proceedings of the International Conference on Mechanical Transmissions*, Chongqing, China, 44-49, 2001.
[16] Troha, S.: *Analysis of a planetary change gear train's variants*, Ph.D. Thesis, Faculty of Engineering, University of Rijeka, Rijeka, 2011.
[17] Karaivanov, D.P., Troha, S.: Optimal Selection of the Structural Scheme of Compound Two-Carrier Planetary Gear Trains and their Parameters, pp.339403, In: Radzevich, S.P., (Ed.), *Recent Advances in Gearing: Scientific Theory and Applications*, First Edition, Springer, Cham, ISBN 9783030646370, 2022
[18] Arnaudov, K., Karaivanov, D.: Systematik, Eigenshaften und Moeglichkeiten von zusammengesetzen Mehrsteg-Planetengetriebe. *Antriebstechnik*, Vol. 5, pp. 58-65, ISSN 0722-8546, 2005
[19] Karaivanov, D. P., et al.: Analysis of Complex Planetary Change-Gears Through the Torque Method, *Proceedings of XIII International Congress "Machines, Technologies, Materials" 2016*, Borovets, Bulgaria, Vol. 25, No. 3, pp. 51-55, 2016.
[20] Vrcan, Ž. et al.: Research into the Properties of Selected Single Speed Two-Carrier Planetary Gear Trains. Journal of. Applied and. Computational. Mechanics, Vol. 8, No. 2, pp. 699–709, ISSN 2383-4536, 2022
[21] Pavlović, A., Fragassa, A., Geometry optimization by FEM simulation of the automatic changing gear, Reports in Mechanical Engineering, Vol. 1, No. 1, pp. 199-205, ISSN 2683-5894, 2020
[22] Handschuh, R F., Epicyclic Gear Trains, In: Wang, Q.J., Chung, Y.W. (Eds.), *Encyclopedia of Tribology*, Springer, Boston, MA, ISBN 9780387928982, 2013.
[23] Janovsky, L.: *Elevator Mechanical Design*, Third Edition, Elevator World, Mobile, AL, ISBN 978-1886536265, 2011.

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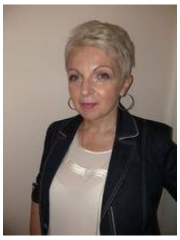

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GEAR TOOTH DAMAGE QUANTIFICATION OF PLANETARY GEARBOX

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Monika LUTOVSKA

Abstract: *The purpose of this paper is to create a scheme for measuring damage to the tooth of the gears based on the analysis of the WVD energy components. The WVD's analysis in this paper is based on image processing techniques, especially on the moments of the images.*
First, we begin by calculating the moments used to describe the geometry of a picture. Based on the analysis of the presented examples, only a few features of all possible moments of the images are easily analyzed for analysis. It has also been shown that the joint probability density of two Gaussian arbitrary variables can be used to approximate the energy distributions most commonly encountered in WVD images. In particular, the WVD image can be presented with acceptable accuracy through a set of Gaussian functions of a common probability.
In order to analyze the individual energy components of the WVD, this paper created a method for extracting the energy components from the WVD image.
Each WVD component can then be analyzed according to the features of the moment and be classified either as an error component or as a component without error. The sum of the energy contained in all components of the fault of the WVD images can be used to measure the extent of damage to the gears. Finally, we will test the error detection and quantification procedures for the experimental vibration data of the BREVINI EM1010 reducers.

Keywords: *Vibration; WVD distribution; image processing; Fast Fourier Transformation; gear; damage.*

1. INTRODUCTION

The gearbox health monitoring is a particular example of the problem where the solution has been intensively sought by the industry. Even small fault in the gear transmission system can quickly develop into a dangerous failure mode. Current on-board condition monitoring system for gear transmission system often fail to provide sufficient time between warning and failure in order to implement the safety procedures. On the other hand, inaccurate interpretation of operational conditions may result in false alarms and unnecessary re-pairs and downtime. The desired improvements in the machinery safety necessitate the technological advancement of health-monitoring systems and procedure.
The advancements in the past research aimed to find a reliable monitoring strategy for the gear transmission system. For the last two decades, various fault detection procedures have been used. Visual inspections of the gearbox have been found to be mostly impractical. Microfaults cannot be easily detected visually unless costly, specialized equipment is used, and it is practically impossible to examine gear transmission during operation. Currently, visual inspection is used mainly after machine failure has already been experienced. Another widely used approach is the analysis of fluid lubricant for debris particles and changes in chemical content. Although this method can provide some use-full information about the current gear transmission conditions, it might not indicate the locations and modes of failure of the gears. One of the most promising procedures for detecting incipient faults in gears is the vibration analysis. Vibration analysis does not re-quire a shutdown of the rotating machinery, thus, it can be carried out on-line by a computer-based machine health monitoring system. Usually, the acquired vibration measurements are processed by a selected method in order to detect the gear fault or failure. The interpretation of the processed vibration data, in some cases, may require the extensive past experience of a re-searcher or maintenance engineer. The difficulty in the interpretation of the processed vibration data has impeded the widespread application of such the health monitoring methods in practice.
The primary goal of the signal processing for the machine health monitoring is to aid the fault detection and classification. The signal processing methods for machine health monitoring can be classified into time domain analysis, frequency domain analysis and joint time-frequency domain analysis. The Wigner-Ville Distribution (WVD), wavelet transform (WT) and short

time Fourier transform (STFT) are examples of the joint time-frequency signal representations. The major difference among these transforms is their resolution properties along time and frequency scales. The joint time-frequency analysis provides the information about the vibration energy changes in the system under the given operation conditions. The joint time-frequency distribution of the faulty fear shows the vibration energy dispersion at times when damaged gear tooth is in mesh. Such energy changes in time can be detected by conventional FFT power spectrum analysis as the appearance of sidebands near the gear mesh frequency only at the advanced stage of damage in the system. The joint time-frequency distribution provides an interactive relationship between time and frequency during the period of the time data window, which reveals the damage at a much earlier stage. The WVD is the most general time-frequency analysis techniques as it provides qualitatively the best resolution along both time and frequency scales in comparison with other transforms (WT, STFT). The WVD is a non-linear transform (a quadratic type), and therefore generates interference terms between signal components [5]. The interference terms often obscure the details of the WVD structure and make the interpretation of the WVD difficult. Many researchers of the WVD for gear diagnostics introduced the techniques (windowing function) to increase the WVD resolution and improve its gear fault detection capabilities [4].

2. WIGNER-VILLE DISTRIBUTION AND GEAR FAULT DETECTION PARAMETERS

The Wigner-Ville Distribution (WVD) is a general time-frequency analysis technique that provides good resolution along both time and frequency scales in comparison with other joint time-frequency transforms such as short time Fourier Transform (STFT) and wavelet transforms. However, the direct application of the WVD to the analysis of the vibration signals is not as straightforward as it may seem. The extensive studies in signal processing have been made to address the problems associated with the computation of the WVD. To avoid the aliasing the problem arising in the computation of the WVD, the original real signal is transformed into a complex analytic signal [6].

Another major obstacle in the application of the WVD is due to its non-linear behavior. The non-linearity of the WVD causes the interference between different signal components. As a result, the appearance of the interference terms in the WVD greatly complicates its interpretation [2].

The WVD can be written as

$$W_{xx}(t,f) = \int_{-\infty}^{+\infty} x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi f\tau}d\tau, \quad (1)$$

where $W_{xx}(t,f)$ is the Wigner-Ville distribution of a complex continuous time analytic signal x(t), t is a time variable and f is a frequency variable. In order to suppress the interference terms in the WVD, a weighting function is added to calculation of the WVD kernel. In the continuous case, the WVD with the added weighting function $\mu(\tau)$ is

$$W_{xx}(t,f) = \int_{-\infty}^{+\infty} x(t+\tau/2)x^*(t-\tau/2)\mu(\tau)e^{-j2\pi f\tau}d\tau,$$

$$\mu(\tau) = h\left(\frac{\tau}{2}\right)h^*\left(-\frac{\tau}{2}\right)$$

$$h(\tau) = C\exp(-\sigma^2\tau^2) \quad (2)$$

where, C and σ are real positive constants. Although process may decrease the resolution of the distribution, it reduces the repetition of the WVD in the time domain, and, thus makes the interpretation of the WVD easier.

The Wigner-Ville distribution satisfies the frequency marginal condition

$$|X(\omega)|^2 = \frac{1}{2\pi}\int |W_{xx}(t,f)|dt. \quad (3)$$

where $|X(\omega)|^2$ is the energy density spectrum and ω is the circular frequency.

This equation means that the integral of the WVD over the time variable at a certain frequency ω yields the energy density spectrum of x(t) at this frequency. The WVD also satisfies the time marginal condition

$$|x(t)|^2 = \frac{1}{2\pi}\int |W_{xx}(t,f)|d\omega. \quad (4)$$

This means that the integral of the WVD over the frequency variable at a certain time t yields the instantaneous signal power at that time. These properties indicate that the WVD can be interpreted as the energy distribution of signal x(t) in time and frequency.

The problem with using this energy distribution is that the WVD is not necessary a positive function at each point on the time-frequency domain. From the energy concept, it would be more convenient to work with a positive function as in the case of the magnitude of FFT. The WVD can be artificially made positive by simply calculating its absolute value at each point. Practical experience shows that the use of absolute values of WVD function simplifies the analysis and display of the distribution. It also allows the common interpretation of the WVD as an energy density or intensity of a signal simultaneously in time and frequency. From this point on, the absolute value of the WVD function is referred to simply as the WVD.

Using the energy density interpretation of WVD, the signal energy at time t and frequency f contained in cell dt by df can be found as $|W_{xx}(t,f)|dtdf$. Thus, the total energy of the signal is defined here through the WVD by integration of the WVD over the time-frequency plane as

$$E = \iint |W_{xx}(t,f)| dtdf \quad (5)$$

Other important signal characteristics that can be defined from the WVD include the instantaneous energy of the signal, or signal power

$$P(t) = \int |W_{xx}(t,f)| df. \quad (6)$$

When a single gear tooth develops a significant defect, a peak appears in the vibration signal. A statistical parameter called kurtosis is used to detect the presence of a major peak in the vibration signal. Kurtosis is a 4^{th} order statistical moment, which measures the peak or flatness of the distribution. The normalized kurtosis for a distribution y(t) given its N values y_1, …..y_N measured at times t_1….t_N can defined as

$$NK(y(t)) = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_i - \bar{y}}{\sigma}\right)^4 - 3, \quad (7)$$

where $\bar{y}$ is mean value, and σ is the standard deviation of y(t).

Kurtosis defined by equation (7) is zero for a normal distribution and -1.5 for pure sine wave. Kurtosis is often defined without the term -3 in equation (7), and, in that case, is 3 for normal distribution. Kurtosis is a non-dimensional quantity. It is positive for a distribution consisting of a sharp single peak and is increasing with an increase in peak of a distribution. This property of the kurtosis was employed in construction of the gear fault detection parameter (NP4).

To utilize the sensitivity of the WVD to signal changes let us define a parameter NP4 as a normalized kurtosis of signal power P(t) given by Equation (8) as

$$NP4 = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{P(t_i) - \bar{P}}{\sigma}\right)^4 - 3, \quad (8)$$

where σ is the standard deviation of P(t). NP4 is a non-dimensional parameter. The parameter NP4 depends only on the shape of the power distribution P(t). Rescaling of the original vibration signal x(t) by multiplying it by a constant does not affect the value of NP4. The same statement is true for any scaling of the signal power P(t). Multiplication of the signal power by a constant does not change the value of the parameter NP4. In short, the parameter NP4 is invariant to scale transformation. The scale invariance property of this fault detection parameter greatly simplifies its practical utility as can be seen later on numerical examples. Most of the rotating machinery components including gearboxes produce complex vibration signal. Some of these vibration components might indicate faulty conditions if they are viewed on the appropriate signal energy scale without being attenuated by the signal components with a higher energy content.

Let us introduced a possible fault detection strategy with NP4 parameter [1].

Table 1. Strategy for fault detection

1. Calculate NP4(0)
2. If NP4(0)>0, set a fault alarm.
3. If NP4(0)<0 but NP4(0)>-1, a multiple gear teeth fault condition possible.
4. Calculate NP4(1) for confirmation of NP4(0).
5. If NP4(1)>0 and NP4(0)>0, a fault alarm is confirmed for gear tooth damage
6. If NP4(1)<0 and NP4(0)<0, do not set a fault alarm.
7. If NP4(1)>1 and NP4(0)<0, set a fault alarm for possible multiple gear teeth damage. This fault alarm is not confirmed by both NP4(0) and NP4(1).

The primary goal of the parameter NP4 is to detect a gear tooth damage. It is expected that NP4 can provide a warning before the multiple gear teeth become damaged. This strategy can be refined by calculating the residual signal of higher order, setting the thresholds other than 0 and -1, etc.

3. EXPERIMENTAL SETUP

The experiment is illustration on Figure 1. The test gearbox is planetary gearbox of BREVINI gear units-standard series. The planetary gear units shown in this test rig have one stage consists of an internal gear meshing with 3 planetary gears mounted on the planet carrier and have the ring gear fixed to the stationary housing. The planet carrier is connected to the output shaft of the gear unit.

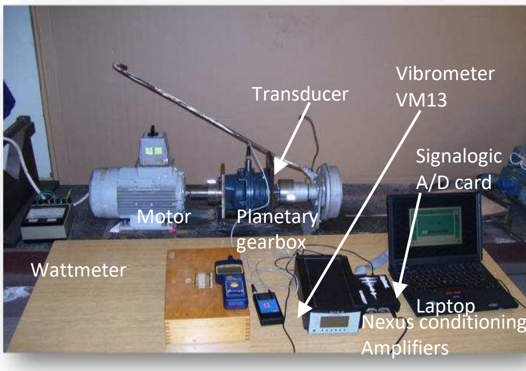

Fig.1 Test rig

Two identical series of the experiments were carried out the gear test rig under various loading conditions: 750W and 3000W [1]. First two experiments used a tail gear transmission in perfect, undemaged conditions, and other two experiments used a tail gear with a single damaged gear tooth as shown in Figure 2.

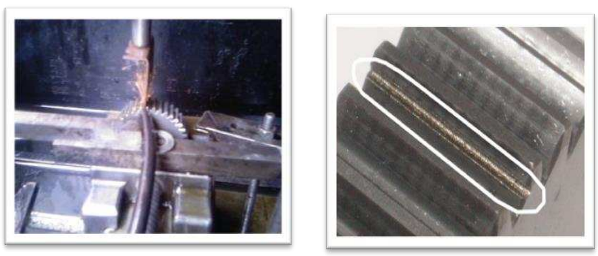

Fig.2 Damage gear tooth

The test gearbox operates at a nominal pinion speed of 1500 rpm (25Hz), thus the meshing frequency is 340Hz. The measurement was taken with one transducer mounted in stationary housing of planetary gearbox. The vibration signals were sampled at 8000Hz. The signal used in this study were recorded with Hypersignal acoustic DSP Software ver.4.31.

4. ANALYSIS THE EXPERIMENTAL DATA

A gear vibration signal for all presented cases was processed in the following manner. First, the WVD of the vibration signal was obtained and displayed. Then, a parameter NP4(0) was calculated for the signal power distribution. Secondly, the WVD for the 1-st order residual vibration signal was calculated as well as a corresponding parameter NP4(1).

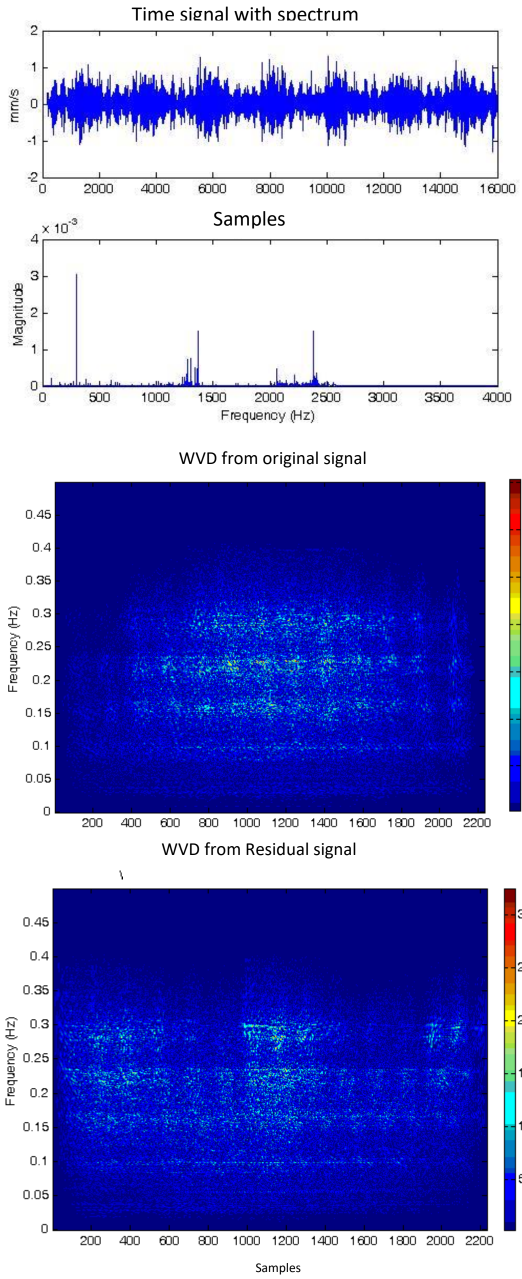

Fig.3 WVD of the original and 1-st order residual gear vibration signal

It was expects that NP4(1) would confirm the result of NP4(0) in the case of the single gear tooth damage. The results of the calculations for the gear in good condition are presented in Figures 3 and Figures 4.

From Figure 4 we have the fault detection parameter NP4 was negative in both cases for the gear load 3000W. The WVD in Figure 4 does not detect any large area of the vibration energy concentration . The parameter NP4 is: NP4(0)=-3.064 and NP4(1)=-3.923. The fault detection strategy based only on the results of the parameter NP4(0) is do not set a fault alarm (rule 6 of Table 1).

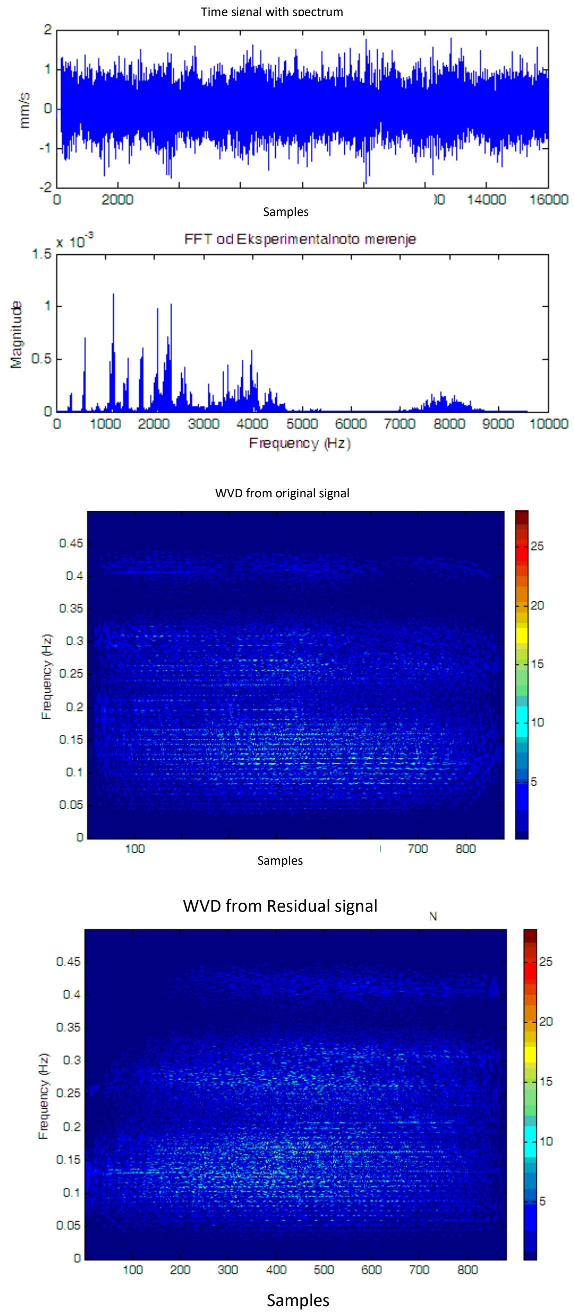

Fig.4 WVD of the original and 1-st order residual gear vibration signal

The results of the calculations for the gear with a single damaged gear tooth are presented in Figures 5 and Figures 6. In figure 5 the parameter NP4(0) accepted small positive number 0.0233 for the nominal power from motor of 750W. Parameter NP4(1) for residual signal is

0.12. If we used the fault detection strategy we have NP4(0)>0 set a fault alarm (role 2 of Table 1) and because NP4(1)>0 the result is fault alarm is confirmed for gear tooth damage.

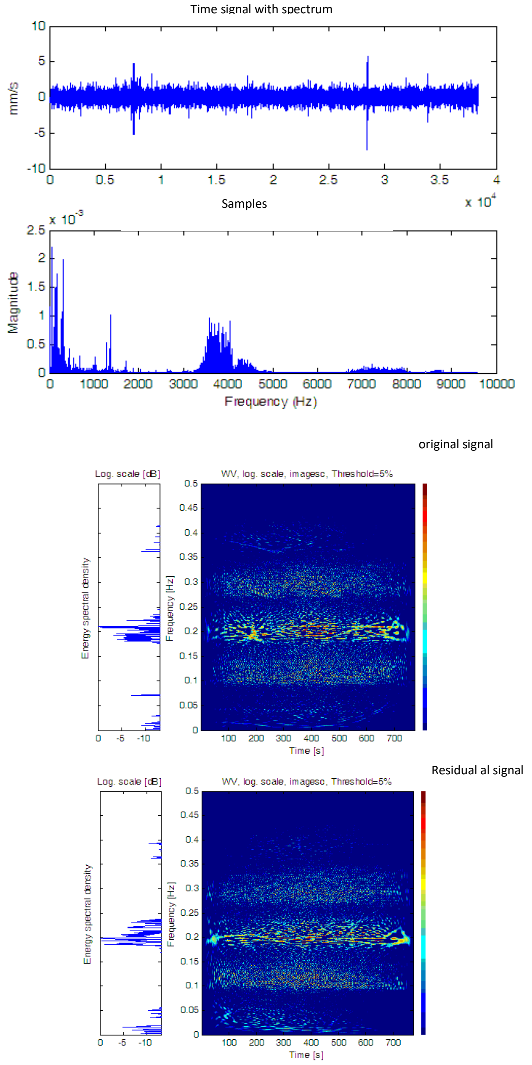

Fig.5 WVD of the original and 1-st order residual gear vibration signal

As shown in Figure 5, a faulty gear tooth produced energy concentration around gear mesh frequency at the location of damage between 150º and 280º revolution of the gear.

In figure 6 the parameter NP4(0) accepted positive number 0.1152 for the nominal power from motor of 3000W. Parameter NP4(1) for residual signal is 1.1224. If we used the fault detection strategy we have NP4(0)>0 set a fault alarm (role 2 of Table 1) and because NP4(1)>0 the result is fault alarm is confirmed for gear tooth damage.

The parameter NP4(1) in figure 6 was increasing with the progression of single gear tooth damage. The location of damage is between 100º and 180º.

5. CONCLUSION

This steady has documented the results of the application of WVD to experimental vibration data obtained from gears with various degrees of damage as well as under various loading conditions. The fault detection strategy based on statistical parameter NP4 was tested on the experimental data. It has been shown that the gear fault detection parameter NP4 is sensitive to a single gear tooth damage and can use to detect the gearbox faults or abnormalities in the performance of the rotating machinery.

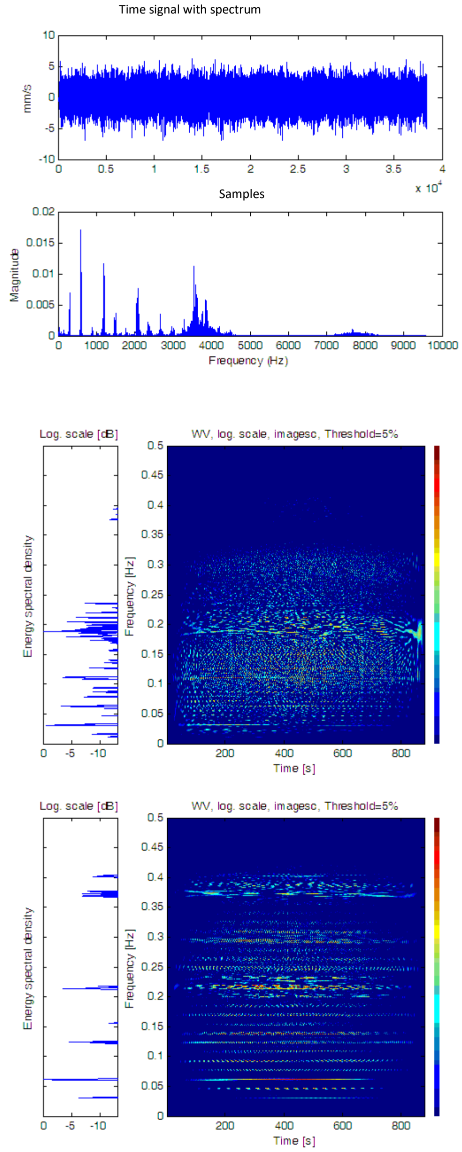

Fig.6 WVD of the original and 1-st order residual gear vibration signal

The reliability of the fault detection parameter NP4 is increased by applying it to both the original and 1-st order residual vibration signal. The distinct features of the fault detection parameter NP4 from other fault detection parameters, such as figures of merit are: It does not compare a measured gear vibration signal with an ideal one. Thus, the parameter NP4 can work without a long recorded vibration history of the gear; It can possibly the severity of the damage, and it untilizes the information content about the vibration energy distribution given by time-frequency domain analysis.

REFERENCES

[1] Trajcevski R.Lj., "Detection of the early fault of the gear tooth damage in a planetary gear with analysis the vibration signatures", *Phd Dissertation*, July 2008.

[2] Geramitcioski T.,Trajcevski Lj., "Derive the fault factor for a gear pair with time varying meshing stiffness", *International conference Power Transmissions '03* Varna, Bulgaria, 11-12. September 2003.

[3] F. K. Choy, S. Huang, J. J. Zakrajsek, R. F. Handschuh, D. Townsend,"Vibration signature analysis of a faulted gear transmission system " *Technical Report NASA TM-106623*, NASA, 1994.

[4] P. D. McFadden and I. M. Howard. "The detection of seeded faults in an epicyclic gearbox by signal averaging of the vibration", *Technical Report ARL-PROP-R-183, Australian Depart-ment of Defense: Aeronautical Research Laboratory*, October 1990.

[5] S.T.Lin, P.D.Mc Fadden, "Vibration analysis of gearboxes by the linear wavelet transform, *2nd International conference on gearbox noise, vibration and diagnosis,* 1995,pp.59-72

[6] Shin, Y.S.,Jean, J.J., "Pseudo Wigner-Ville Time-Frequency Distribution and Its Application to Machinery Condition Monitoring", *Journal of Shock and Vibration, Vol.1*, No.1, pp.65-76,1993

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EXPERIMENTAL AND NUMERICAL ANALYSIS OF MECHANICAL PROPERTIES OF CARBON FIBER-REINFORCED POLYMER GEARS

Fatih KARPAT
Fatmagül DEDE
Tufan Gürkan YILMAZ
Onur Can KALAY

Abstract: *Composite materials emerge as better alternatives for replacing metallic gears in gear drive applications. Because composites have better mechanical properties, such as resistance to abrasion, don't require lubrication, produce less noise, and have high strength/weight ratios. It is considered that using composites in gears, which are an important machine element, will be extremely advantageous. This research aims to identify the mechanical properties of carbon fiber-reinforced polymer (CFRP) gears. To this end, a composite plate was created by vacuum infusion employing twill woven carbon fiber cloth as a reinforcing element and epoxy resin as a matrix element. This manufactured plate was used to cut the gear profile, which was then put through its paces. The tensile test was carried out to determine the strength of the samples cut from the plate. After the strength tests, numerical analysis of the gear sample produced by the finite element method was performed. The results showed that composite gears would offer a good alternative to metal gears.*

Keywords: *CFRP gears; composite materials; vacuum infusion; finite element method; mechanical testing*

1. INTRODUCTION

The increasing need for rigid and lightweight structures has led researchers and industry to composite materials. Composite materials have gained momentum in recent years as a viable alternative to traditional materials such as steel or aluminium alloys, in aerospace, automotive and other industrial applications. However, due to its advantages over metal gears, the use of polymer materials in gear transmissions is increasing. Polymer gears have been widely used in recent years, where the use of metal gears would not be very economical and typically with lower load requirements. Polymer gear transmissions are significantly less in weight than metal gears because the material properties of composites are very attractive for weight improvements. In addition, polymer materials have better noise, vibration, and stiffness (NVH) behaviour due to good damping effects.

New environmental regulations have mandated different designs that focus on the global efficiency of the system to reduce greenhouse gas emissions and fuel consumption. One of the strategies developed due to such constraints is to reduce gear transmissions. High-speed fatigue behaviour of autoclave-cured carbon fiber reinforced polymer (CFRP) composite gears researched by "The mechanical properties of fiber-reinforced polymer composites are highly dependent on the strength of the fibers and the matrix and the adhesion between the two." It is important to investigate the performance of woven CFRP gears because of their potential to further increase load bearing capacity and wear resistance compared to short fiber reinforced polymer gears [1-2].

The thermal and mechanical properties of laminated CFRP composites are affected by the properties of their key components, such as the polymer matrix and reinforcing fibers, as well as the method of preparation of the laminate. Zhang et al (2016) performed quasi-static and dynamic tensile tests on unidirectional woven CFRP samples. While a characteristic effect of strain rate on tensile modulus and strength was observed in dynamic load tests, the significance of this correlation decreased in quasi-static tests [3].

Gear performance depends on the tribological behaviour of the gear pair at the contact interface. Bijwe and Sharma studied the effect of carbon fiber (CF) content ratio on the mechanical and tribological properties of CFRP with polyetherimide (PEI) thermoplastic matrix. With a fiber content of 65%, it has reached optimum results in mechanical and tribological properties [4].

As noted above, many possibilities exist to further improve the thermomechanical and tribological properties of composite gears. CFRPs can provide high mechanical strength, good thermal stability, high thermal conductivity and favourable tribological properties if a suitable manufacturing technique is used. This makes them ideal

candidates for gears and other power transmission components.
The purpose of this study is to make a comparison between metal and CFRP gears. It is aimed to fill the gap between the two gear types by using vacuum infusion cured, laminated CFRP gears. It is known that the use of polymer materials in gear transmissions is increasing due to their advantages over metal gears. Nevertheless, the subject contains gaps that are worth investigating and examining.

2. MATERIAL AND METHOD

In this section, design of spur gear is realized with programming mathematical equations. The parameters of rack cutter that generates spur gear are illustrated in Figure 1.

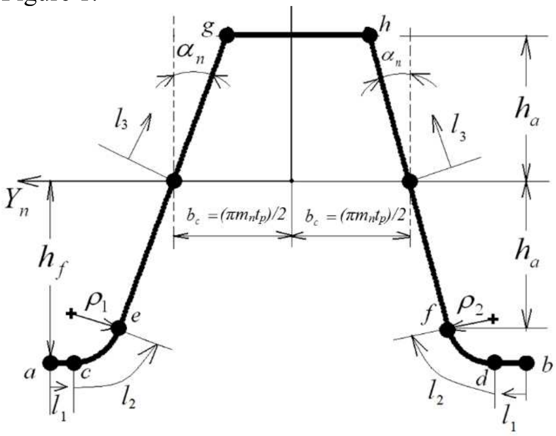


Fig.1. Parameters of rack

The equation of rack regions is given as matrix form in the following expressions;

ac-bd region

$$R_n^1=\begin{bmatrix} -h_f \\ \pm(\frac{\pi m}{2}-l_1) \\ 0 \\ 1 \end{bmatrix} \tag{1}$$

$$0<l_1<b_c-h_f\tan\alpha_n+\rho_{1,2}\tan\alpha_n-\rho_{1,2}\sec\alpha_n \tag{2}$$

ce-df region

$$R_n^2=\begin{bmatrix} -h_f+\rho_{1,2}-\rho_{1,2}\cos l_2 \\ \pm(b_c+h_f\tan\alpha_n-\rho_{1,2}\tan\alpha_n+\rho_{1,2}\sec\alpha_n-\rho_{1,2}\sin(l_2)) \\ 0 \\ 1 \end{bmatrix} \tag{3}$$

$$0<l_2<(\frac{\pi}{2}-\alpha_n) \tag{4}$$

eg-fh region

$$R_n^3=\begin{bmatrix} l_3\cos\alpha_n \\ \pm(b_c-l_3\sin\alpha_n) \\ 0 \\ 1 \end{bmatrix} \tag{5}$$

$$\frac{-h_a}{\cos\alpha_n}\leq l_3\leq\frac{h_a}{\cos\alpha_n} \tag{6}$$

Where, m is the module, z is the teeth number, $\alpha_{n1,2}$ is the pressure angle on sides, h_f is the dedendum, h_a is the addendum, $\rho_{1,2}$ are the tip radii, $l_{1,2,3}$ is the design parameter of cutter, b_c is half thickness of rack on pitch line.

$$n_n^i=\frac{\frac{\partial R_n^i}{\partial l_i}\times k_n}{\left|\frac{\partial R_n^i}{\partial l_i}\times k_n\right|} \qquad i=1\text{-}3 \tag{7}$$

Where k_n unit normal vector of Z direction.
According to the gearing theory, direction of sliding velocity vector between pinion and gear is parallel with tangent vector of common meshing point. Of course, it is always perpendicular to common normal vector. This expression is presented in Eq. (8).

$$n_n^i\cdot v_{relative}=0 \qquad i=1\text{-}3 \tag{8}$$

During the generating process, the rack cutter makes a linear motion as $r_{p1}\times\varphi_1$ whilst the gear as workpiece revolves as $Ø_1$. $S_1(X_1, Y_1)$ is the coordinate system of workpiece. Relationship between cutter and workpiece is shown in Figure 2.

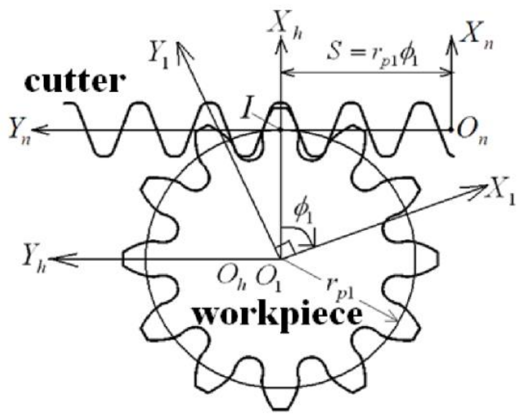


Fig.2. Relation between cutter and gear

Coordinate transformation matrix between rack cutter and workpiece is presented in the following equations.

$$M_{1n}=\begin{bmatrix} \cos(\emptyset_1) & -\sin(\emptyset_1) & 0 & r_{p1}\emptyset_1\sin(\emptyset_1)+r_{p1}\cos(\emptyset_1) \\ \sin(\emptyset_1) & \cos(\emptyset_1) & 0 & -r_{p1}\emptyset_1\cos(\emptyset_1)+r_{p1}\sin(\emptyset_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$M_{1n}=\begin{bmatrix} \cos(\emptyset_1) & -\sin(\emptyset_1) & 0 & r_{p1}\emptyset_1\sin(\emptyset_1)+r_{p1}\cos(\emptyset_1) \\ \sin(\emptyset_1) & \cos(\emptyset_1) & 0 & -r_{p1}\emptyset_1\cos(\emptyset_1)+r_{p1}\sin(\emptyset_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(9)

$$R_1^i = M_{1n}{}^i R_n{}^i \qquad i=1\text{-}3 \qquad (10) \quad (10)$$

Where M_{1n} is the coordinate transformation matrix and R_1 is matrix of involute spur gear, r_{p1} is pitch diameter.

With programming Eq. (1-10) in MATLAB program, the design points of involute spur gears are obtained. These points are exported to CAD to generate FE model. In Figure 3, design phases are given.

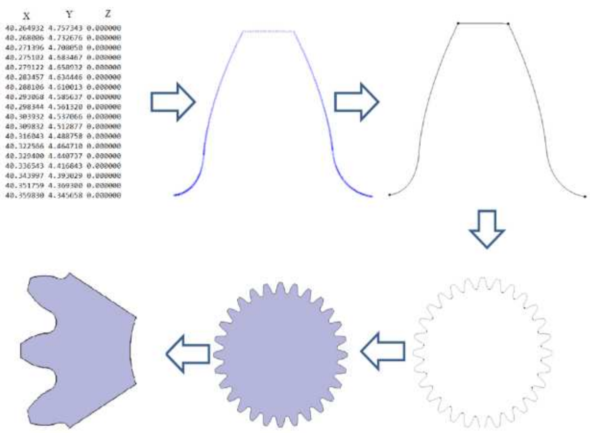


Fig.3. Design phases

First, sample plates were produced using epoxy resin with the fiber planned to be used. The carbon fiber fabric used in the study was 3K twill woven with a density of 245 gr/cm² and the epoxy used had the Duratek brand DTE 1200/DTS 2110 code. After determining the fabrics, resin, and vacuum values to be used, sample plates of 45*50 cm were produced by applying the steps of the vacuum infusion method. Glass plate was used as a mold during production. The composite sheet was removed from the mold after the infusion process and the necessary curing time, and the sample was cut in line with the TS EN ISO 527-4 tensile test standard. End-tab was adhered to the cut samples with epoxy adhesive and made ready for the tensile test (Fig. 4).

Fig. 4. CFRP samples prepared for tensile testing

After the above-mentioned processes, tensile tests were applied. These tests were carried out on the Besmak universal tensile/compression test device. According to the results obtained, the modulus of elasticity was 62.85 GPa and the tensile strength was 616,085 MPa for the CFRP sample.

3. FINITE ELEMENT ANALYSIS

In this section, finite element analyses were conducted for specific gear parameters. In Table 1, the parameter of case studies is illustrated.

Table 1. Gear parameters

Parameters	***Case I***	***Case II***	***Case III***
Module-m (mm)	2	2	2
Teeth number(z)	20	20	20
Pressure angle-α_n (°)	20	20	20
Addendum-h_a (×m)	1	1	1
Dedendum-h_f (×m)	1.25	1.25	1.25
Cutter tip radius- $\rho_{1,2}$ (×m)	0.38	0.38	0.38
Face width- b (mm)	1	1	1
Rim status	Solid	Thin	Solid
Material	Steel	Steel	CFRP

Three gear teeth models prepared for finite element analyses. Meshing force (100 N) was applied at tip of tooth. Fixed support was given lateral sides and shaft hole. Boundary condition and mesh structure are presented in Figure 5.

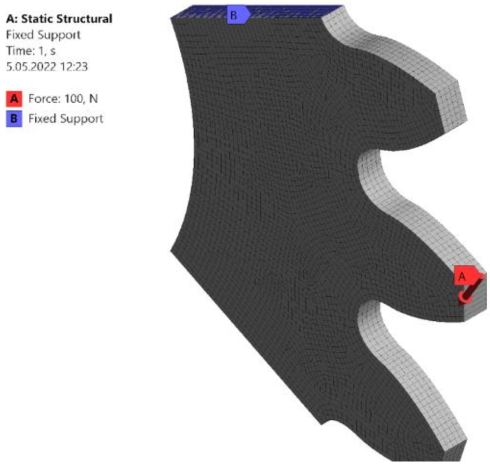
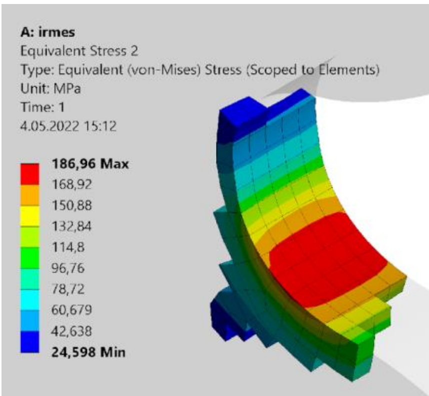
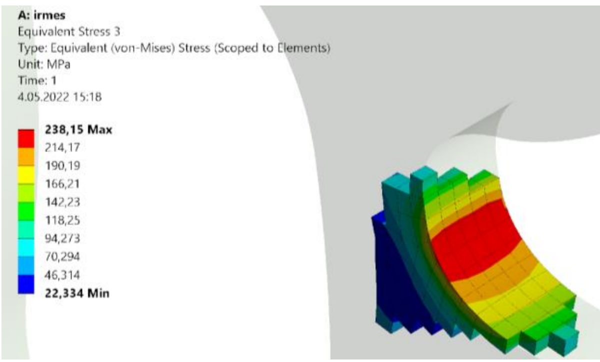


Fig. 5. Mesh and boundary conditions

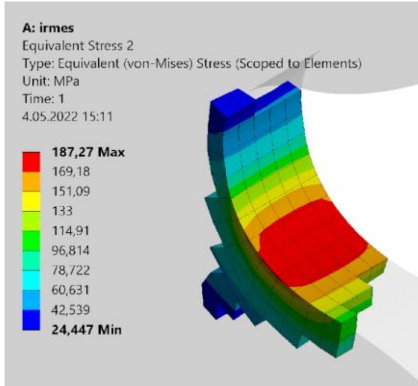
Hexahedral mesh type is used for discrete FE body with 0.2 mm edge length. For Case I and II, Young's modulus and Poisson's ratio of material is taken as 210 GPa and 0.3, respectively. For Case III, CFRP material is modelled as isotropic material. Young's's modulus of CFRP is obtained as 62.85 GPa in the tensile test. For this reason, this value is taken as directly in numerical modelling. In Figure 6, the root stress results are given.



a) **Case I**



b) **Case II**

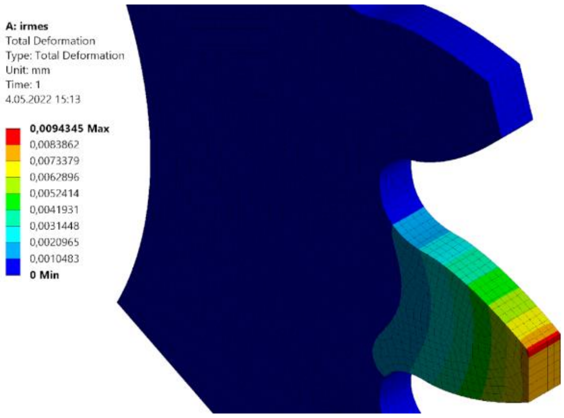


c) Case III

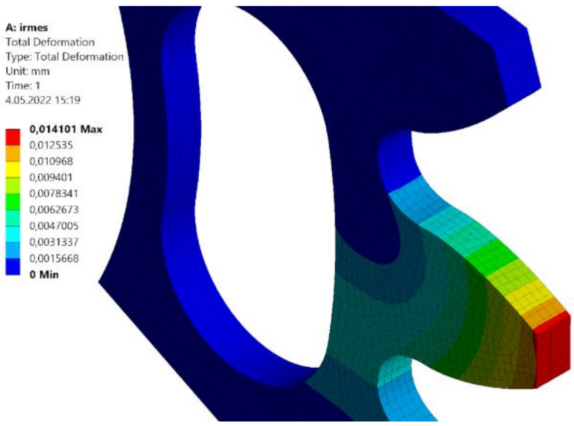
Fig.6. Root stress results

According to results, the material change slightly makes differences in root stress when the root stress results is examined for Case I and Case II (<1%). On the other side root stress of thin rimmed steel spur gear is approximately 30% higher than CFRP gear.

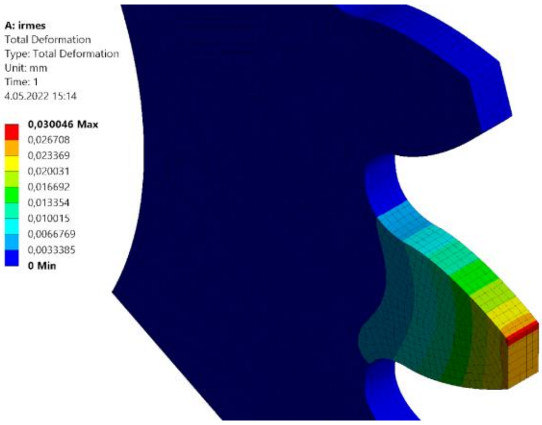
Tooth deformation is another key parameter for spur gear performance. For this reason, tooth deformation values should be investigated. In Figure 7, deformation results are given for each case



a) **Case I**



b) **Case II**



c) **Case III**

Fig.7. Tooth deformation results

According to results, the Case I is found as the best option in terms of tooth deformation. CFRP gear deformation value is double of thin rimmed lightweight steel gear. Deformation is closely related with Young's modulus. For this reason, these results are expected.

4. CONCLUSION

In this study, the CFRP gear was compared with steel and light steel gear in terms of stress and deformation. For this aim, the 3D gear model was prepared for finite element analyses. To obtain the Young's modulus of composite material, tensile test was conducted. According to finite element analyses, the following points were obtained.

- CFRP gear is better than thin rimmed lightweight steel gear in terms of root stress. The root stress difference between solid rim steel gear and CFRP gear is found as rather low.
- CFRP gear is found as worst option in view of tooth deformation. Yet, when taken into consideration of the whole gear weight status, CFRP gear (1.40 gr) can be more advantageous than steel (6.6 gr) and lightweight steel gear (5 gr). Based on this fact, the tooth deformation of CFRP gear can be decreased with increase the face width.

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REFERENCES

[1] Zorko D, Tavear J, Bizjak M, Sturm R, Bergant Z. High cycle fatigue behaviour of autoclave-cured woven carbon fibre-reinforced polymer composite gears. *Polymer Testing*; 102:107339, 2021.

[2] Cerne, B., Bergant, Z., Sturm, R., Tavcar, J., Zorko, D. Experimental and numerical analysis of laminated carbon fiber-reinforced polymer gears with implicit model for coefficient-of-friction evaluation. *Journal of Computational Design and Engineering*, 00(0), 1–18, 2021

[3] Zhang, X., Hao, H., Shi, Y., Cui, J., & Zhang, X. Static and dynamic material properties of CFRP/epoxy laminates. *Construction and Building Materials*, 114, 638–649, 2016.

[4] Bijwe, J., & Sharma, M. Carbon fabric-reinforced polymer composites and parameters controlling tribological performance. In J. P. Davim (Ed.), *Wear of Advanced Materials* (Chap.1, pp. 1–60). John Wiley & Sons, Ltd. ISO number of standard (incl. year), Standard Title, 2013.

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INTERFERENCE ANALYSIS OF INTERNAL INVOLUTE SPUR GEAR PAIR

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Božidar ROSIĆ
Mileta RISTIVOJEVIĆ

Abstract: *In this paper, we have considered tip interference and radial interference of internal involute spur gears. Equations of tooth profiles are provided and operating constraints for internal gears are defined. The undercutting and interference of the teeth profiles are the main problems for the practical application of internal gears in planetary gear trains, which requires particular attention in the design of planetary gear trains. The problem of avoiding interference of internal involute spur gears is especially challenging. Therefore, it is necessary to create the corresponding geometric models and express the above requirements by the corresponding functional constraints to verify the engagement condition. The developed geometrical model of the tooth surfaces is most helpful in the analysis of meshing interference, contact, and stress analyzing, manufacturing, measuring, and optimizing internal gear sets. The numerical results are tested by computerized simulation of the meshing of internal involute spur gears.*

Keywords: *internal gear; pinion; interference; design.*

1. INTRODUCTION

Internal gears are a vital part of most transmission systems, especially in planetary gear trains, heavy-duty machines, and mechanisms because of their advantages, such as high gear ratio, high efficiency, and compact structure.

In comparison with an external spur gear, the center distance of an internal spur gear, with the same gear ratio, is much shorter, and thus the constructions are more compact.

Planetary gear trains have a number of advantages as compared to the transmission with fixed shafts. Under similar operating conditions, the planetary transmissions serve longer and produce less noise compared to the fixed shaft transmission. In recent years, many researchers have successfully investigated the surface geometry of spatial conjugate gear pairs [1,2]. The kinematics and geometric relation between the gear and the cutting tool during the profile generation process is the same relation as that developed when a gear meshes with a rack [3]. These analyses have greatly extended our understanding of surface geometry and contact kinematics. In this paper, a geometrical model of the tooth surfaces for the internal gear set is developed, such as the equations of tooth profiles, based on the cutting design parameters of the pinion cutter form. In order to ensure the mounting as well as the correct meshing of the gears, it is necessary to fulfill the requirements regarding their alignment and the clearance between the gears. The undercutting and interference of the teeth profiles can occur during the meshing. Therefore, the above requirements by the corresponding functional constraints, and based upon them, have largely been investigated to identify all relevant values together with the areas of their practical applications [4,5,6].

The main objective of this work is to investigate the operating constraints for internal gears as a function of gear pair parameters.

2. INTERFERENCE ANALYSIS

2.1. Interference type

Interference may occur between internal and external tooth tips of the considered gear pair. According to this, Figure 1 illustrates the mesh of an internal gear and external gear when tip interference is non-existent. As can be seen from the illustration in Fig. 1, the critical point can be considered when the pinion tip intersects the internal gear tip circle.

Condition for the actual clearance angles between the profiles of a tooth pair measured on the addendum circle of the tooth pair must be satisfied.

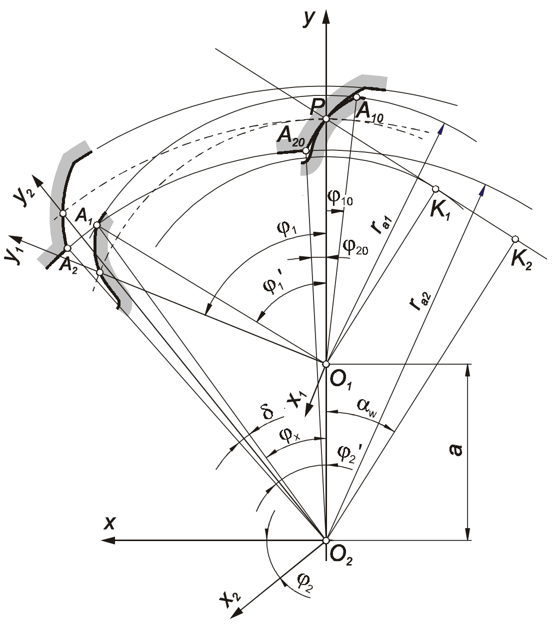

Figure 1. Analysis of tip interference.

Therefore, in order to avoid the tip interference, the following condition is formulated:

$$\delta = \varphi_2 - \varphi_x > 0 . \tag{1}$$

From the geometrical relationships represented in Figure 2. the following equation can be derived:

$$r_{a1}^2 = r_{a2}^2 + a^2 - 2 \cdot a \cdot r_{a2} \cdot \cos\varphi_x , \tag{2}$$

where r_{a1}, r_{a2} denote the tip radii of the pinion and gear, respectively.

The gear ratio gives the relation between the twist angles where the corresponding rotation of the internal gear is given by:

$$\varphi_2 = \frac{z_1}{z_2}\varphi_1 . \tag{3}$$

The angles φ_1 and φ_2 are then calculated as follows:

$$\varphi_1 = \arccos\frac{r_{a2}^2 - r_{a1}^2 - a^2}{2 \cdot r_{a1} \cdot a} , \tag{4}$$

$$\varphi_2 = \varphi_2 - \varphi_{20} , \tag{5}$$

where

$$\varphi_{10} = inv\alpha_{A1} - inv\alpha_w , \tag{6}$$

$$\varphi_{20} = inv\alpha_w - inv\alpha_{A2} , \tag{7}$$

and α_{A1}, α_{A2} denote the pressure angles at the pinion and gear tooth tips, respectively.

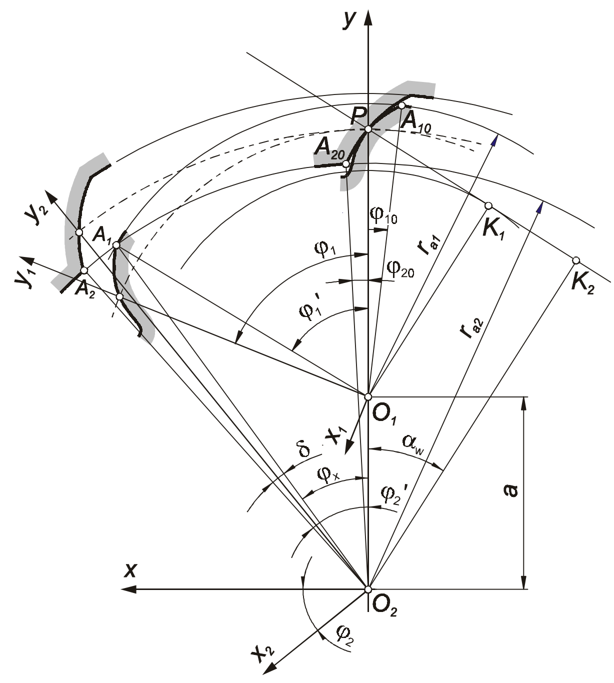

Figure 2. The effect of the rotation of angle φ_1 upon the space requirements.

Tooth profiles of two coupled gears are depicted in Figure 3, where the profile of the pinion gear is shown in the concave area of the internal involute spur gear.

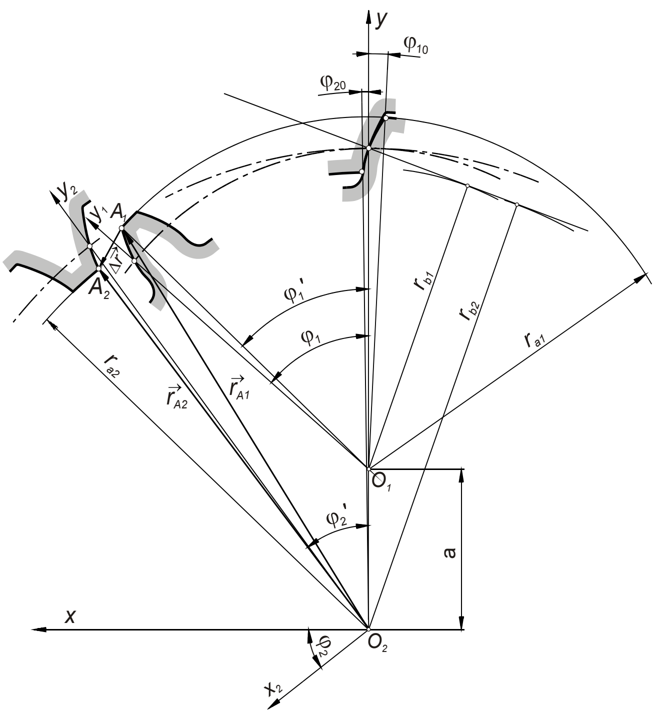

Figure 3. The appropriate radius vector of the tool tips of the pinion and internal gear.

As shown in Figure 3, the radius vector $\Delta\mathbf{r}$ between the points on the tips of the corresponding gear profiles of the considered gear-pair, can be written as follows

$$\Delta \mathbf{r} = \mathbf{r}_{A2} - \mathbf{r}_{A1} = \Delta r_x \cdot \mathbf{i} + \Delta r_y \cdot \mathbf{j}\,, \tag{8}$$

where

$$\Delta \mathrm{r}_x = r_{a2} \cdot \sin\varphi_2\,' - r_{a1} \cdot \sin\varphi_1\,'\,, \tag{9}$$

$$\Delta \mathrm{r}_y = r_{a2} \cdot \cos\varphi_2\,' - (r_{a1} \cdot \cos\varphi_1\,' + a)\,, \tag{10}$$

In connection with that, Figure 4 represents the change of the functional constraint as the function of the rotation of angle, with a different tooth number difference.

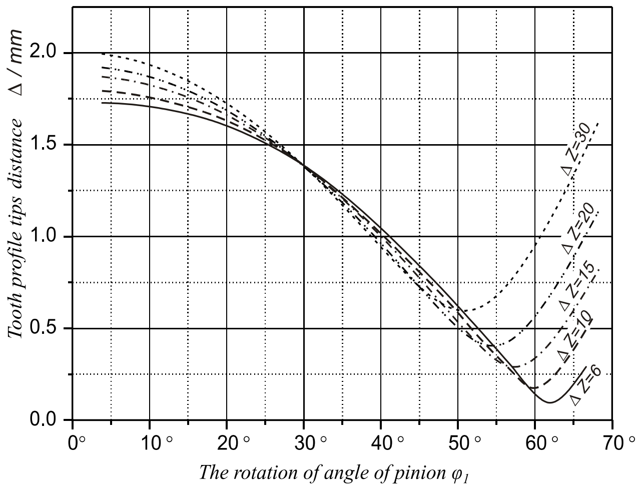

Figure 4. Tooth profile tips distance between coupled gears of the internal gear pair.

Based upon the graphic representation of the results obtained, it follows that the given functional constraint is exceptionally sensitive to the change rotation angle of the external gear-pinion cutter. The tooth number difference is the major influential factor on the clearance angle.
From the required conditions finding the extremum of the expression

$$\frac{\partial \Delta r}{\partial \varphi_1\,'} = \frac{1}{\Delta r}\left[\Delta r_x \frac{\partial(\Delta r_x)}{\partial \varphi_1\,'} + \Delta r_y \frac{\partial(\Delta r_y)}{\partial \varphi_1\,'}\right] = 0\,, \tag{11}$$

We can determine the angle $\varphi_1\,'$ for which we can observe the minimum distance between tooth profile tips between coupled gears of the internal gear pair.
Geometrical interpretation of the Eq. (11) is shown in Figure 5, where the plot is represented as the function of the difference in the teeth of the considered internal gear-pair, for constant increase of profile shift coefficients of internal gears relative to the gear with external gearing.

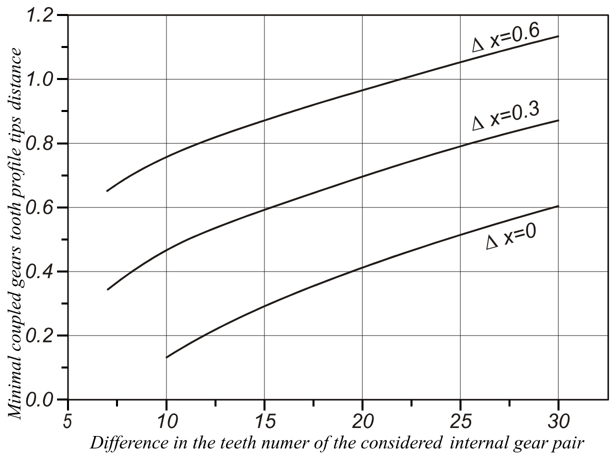

Figure 5. Minimal coupled gears tooth profile tips distance.

Based on the results presented in Figure 5 it can be concluded that the formulated constraint is very sensitive to the increase of profile shift coefficients of internal gears relative to the gear with external gearing, as well as to the difference in the teeth of the considered internal gear pair.
These effects are especially noticeable when:

- the difference in the teeth of the considered internal gear pair is low, i.e., $\Delta z \le 6$, and
- when the increase in profile shift coefficient is $\Delta x \le 3$.

2.2. Radial interference

This type of interference can occur in the process of cutting an internal gear with a pinion cutter as shown in Figure 6.

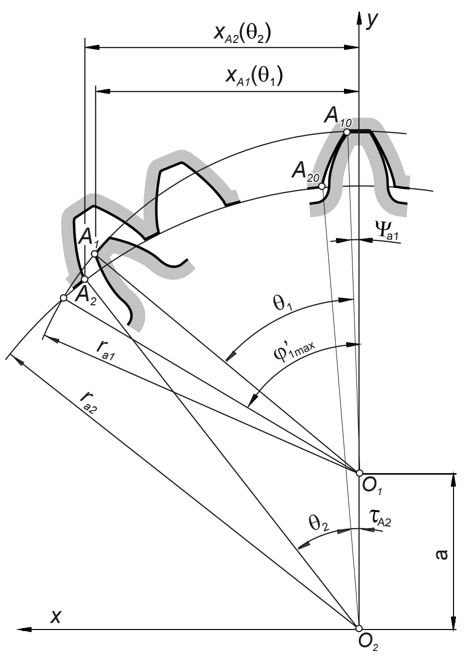

Figure 6. The radial approach of the pinion cutter

The coordinate of the tip of the tooth profile of the pinion cutter on the x-axis can be determined according to the expression

$$x_{A1} = r_{a1} \cdot \sin\left(\theta_1 + \psi_{A1}\right), \tag{12}$$

where the coordinate on the x-ais of the tip of the tooth profile of the internal gear is determined according to

$$x_{A2} = r_{a2} \cdot \sin\left(\theta_2 + \tau_{A2}\right). \tag{13}$$

The functional constraint for the radial interference can be expressed as

$$\Delta_x = x_{A2}\left(\theta_2\right) - x_{A1}\left(\theta_1\right) > 0. \tag{14}$$

After substituting equations (12) and (13) into the expression (14), we can determine the distance between tooth profile tips of pinion and internal gear along the x-axis, according to

$$\Delta_x = r_{a2} \cdot \sin\left(\theta_2 + \tau_{A2}\right) - r_{a1} \cdot \sin\left(\theta_1 + \psi_{A1}\right), \tag{15}$$

where

$$\theta_2 = \frac{z_1}{z_2} \cdot \theta_1. \tag{16}$$

Then, by substituting angle θ_2 into the equation (15), the following expression for the distance between tooth profile tips of pinion and internal gear along the x-axis can be written as follows

$$\Delta_x = r_{a2} \cdot \sin\left(\frac{z_1}{z_2} \cdot \theta_1 + \tau_{A2}\right) - r_{a1} \cdot \sin\left(\theta_1 + \psi_{A1}\right). \tag{17}$$

The minimal distance between tooth profile tips of pinion and internal gear can be determined from the condition of determining the minimum of the expression (17). After taking the first partial derivative of the expression (17), with respect to the variable θ_1 we can obtain

$$\Delta_x\left(\theta_1\right)' = \\ = \frac{z_1}{z_2} \cdot r_{a2} \cdot \cos\left(\frac{z_1}{z_2} \cdot \theta_1 + \tau_{A2}\right) - r_{a1} \cdot \cos\left(\theta_1 + \psi_{A1}\right) \tag{18}$$

The results for the formulated functional constraint as the function of the profile shift coefficients and the difference in the teeth of the considered internal gear pair are presented in Figure 7.

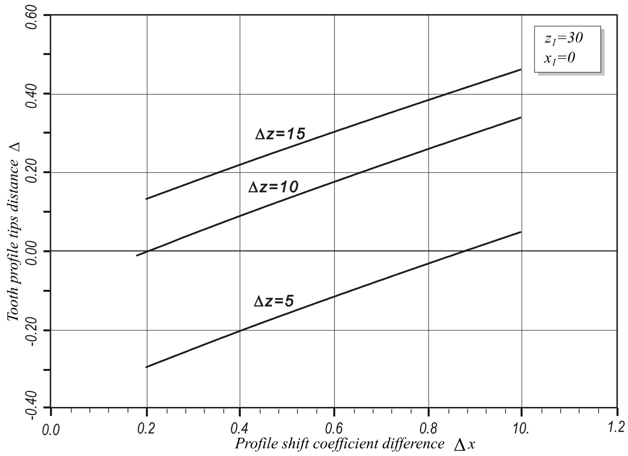

Figure 7. Tooth profile tips distance between coupled gears of the internal gear pair.

Based on the graphical interpretation of the obtained results shown in Figure 7, it follows that the formulated functional constraint is very sensitive to the increase of the profile shift coefficients and the difference in the teeth of the considered internal gear pair. Therefore, the radial interference does not occur if the following conditions are satisfied:

– the difference in the number of teeth of the considered internal gear pair is greater than 15
– the difference in the profile shift coefficient of the internal gear pair is greater than 0.2 and the difference in the number of teeth of the considered gear pair is greater than 10.
– the difference in the profile shift coefficient of the internal gear pair is greater than 0.88 for the difference in the number of teeth of the considered gear pair greater than five.

3. SIMULATION OF MESHING

The kinematics and geometric relation between the gear and the cutting tool during the profile generation process is the same relation as that developed when a gear meshes with a rack. Based on the basic law of conjugate action, the common normal of the surfaces at the contact point must pass through the instantaneous contact points on the surface of the cutting tool.

In order to simulate the conditions of meshing, the coordinate system Ox_1y_1 and Ox_2y_2 that are rigidly connected to pinion 1 and gear 2, respectively as shown in Figure 4. The meshing of the gear tooth surfaces is considered in the fixed coordinate system Cxy that is rigidly connected to the housing.

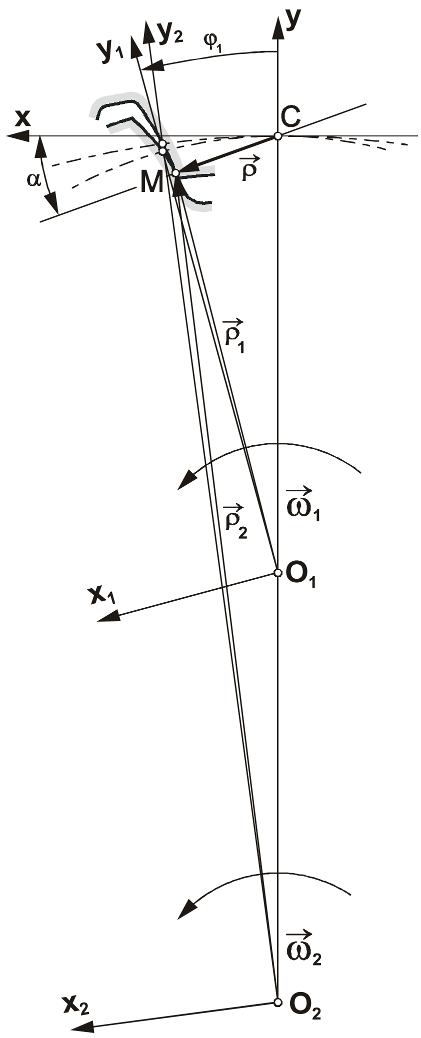

Figure 8. Coordinates systems for the generation of pinion tooth space.

Transforming the coordinate system Ox_1y_1 which is attached to the pinion a cutter to fixed coordinate system Cxy, we can described by:

$$\begin{Bmatrix} \mathbf{i}_1 \\ \mathbf{j}_1 \end{Bmatrix} = \begin{bmatrix} \cos\varphi_1 & \sin\varphi_1 \\ \sin\varphi_1 & \cos\varphi_1 \end{bmatrix} \begin{Bmatrix} \mathbf{i} \\ \mathbf{j} \end{Bmatrix}. \tag{19}$$

At the point of contact, due to the tangency of two contacting gear tooth surfaces, the position vectors and their unit normal of both gear tooth surfaces should be the same.
Therefore, the following equations must be observed [5]:

$$\boldsymbol{\rho}_f^{(p)} = \boldsymbol{\rho}_f^{(g)}, \tag{20}$$

$$\mathbf{n}_f^{(p)} = \mathbf{n}_f^{(g)}. \tag{21}$$

The shape of the pinion tooth is represented in the coordinate system Cxy by the vector equation. Thus

$$\boldsymbol{\rho} = \overrightarrow{CO_1} + \boldsymbol{\rho}_1 = -r_{w1}\mathbf{j} + x_1\mathbf{i} + y_1\mathbf{j}, \tag{22}$$

where r_{w1} denotes the kinematic circle of the pinion cutter.

We transfer the pinion tooth shape to a fixed coordinate system Cxy, using the matrix equation:

$$\begin{aligned} \boldsymbol{\rho}_2 &= \left(x\cos\varphi_2 - y\sin\varphi_2 - r_{w2}\sin\varphi_2\right)\mathbf{i}_2 \\ &\quad + \left(x\sin\varphi_2 + y\cos\varphi_2 + r_{w2}\cos\varphi_2\right)\mathbf{j}_2 \end{aligned} \tag{23}$$

where

$$\begin{Bmatrix} x_1 \\ y_1 \\ t_1 \end{Bmatrix} = \begin{Bmatrix} r\cdot\varphi_1\cdot\cos\varphi_1\cdot\cos^2\alpha \\ -r\cdot\sin\varphi_1\cdot\left(1-0,5\cdot\varphi_1\cdot\sin 2\alpha\right) \\ r\cdot\varphi_1\cdot\cos\varphi_1\cdot\cos^2\alpha \\ -r\cdot\sin\varphi_1\left(1-0,5\cdot\varphi_1\cdot\sin 2\alpha\right) \\ 1 \end{Bmatrix}. \tag{24}$$

The position vector from O_2 to the cutting point, expressed in a fixed coordinate system is given by:

$$\boldsymbol{\rho}_2 = \overrightarrow{O_2C} + \boldsymbol{\rho} = r_{w2}\mathbf{j} + x\mathbf{i} + y\mathbf{j}. \tag{25}$$

By applying the coordinate transformations, the equation of gear tooth surface can be represented in the coordinate system $O_2x_2y_2$ as follows:

$$\begin{aligned} \boldsymbol{\rho}_2 &= \left(x\cos\varphi_2 - y\sin\varphi_2 - r_{w2}\sin\varphi_2\right)\mathbf{i}_2 \\ &\quad + \left(x\sin\varphi_2 + y\cos\varphi_2 + r_{w2}\cos\varphi_2\right)\mathbf{j}_2 \end{aligned} \tag{26}$$

where

$$\begin{Bmatrix} \mathbf{i} \\ \mathbf{j} \end{Bmatrix} = \begin{bmatrix} \cos\varphi_2 & \sin\varphi_2 \\ \sin\varphi_2 & \cos\varphi_2 \end{bmatrix} \begin{Bmatrix} \mathbf{i}_2 \\ \mathbf{j}_2 \end{Bmatrix}. \tag{27}$$

It is practically impossible to present in this paper all the relations between the gear and the cutting tool during the profile generation process.

4. CONCLUSION

In this work, the tip and radial interference of the internal gear pair are investigated. The developed geometrical model of internal gear pair is most helpful in designing, contact and stress analyzing, manufacturing, measuring and optimizing internal gear sets. The numerical results are tested by computerized simulation of the meshing of internal involute spur gears with pinion cutters to demonstrate the developed model.

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REFERENCES

[1] Z. Ou, A. Seireg: Analysis and Synthesis of Circular Arc Gears by Interactive Graphics, *ASME Journal of Mechanisms, Transmissions, and Automation in Design*, MARCH 1986, Vol. 108, pp 65-71.

[2] Colbrune, J. R.: *The geometry of Involute gears*, Springer–Verlag, 1990.

[3] F. L. Litvin, J. Zhang, R. F. Handschuh: Crowned Spur Gears: Methods for Generation and Tooth Contact Analysis – Part I: Basic Concepts, Generation of the Pinion Tooth Surface by a Plane, *Journal of Mechanisms, Transmissions, and Automation in Design,* September 1988, Vol. 110, pp 337-342.

[4] F. L. Litvin, J. Zhang, R. F. Handschuh: Crowned Spur Gears: Methods for Generation and Tooth Contact Analysis – Part 2: Generation of the Pinion Tooth Surface of Revolution, *Journal of Mechanisms, Transmissions, and Automation in Design*, September 1988, Vol. 110, pp 343-347.

[5] F.L. Litvin, R. N. Goldrich, J.J. Coy, Z. B. Zaretsky: Kinematic Precision of Gear Trains, *ASME Journal of Mechanisms, Transmissions, and Automation in Design*, SEPTEMBER 1983, Vol. 105, No.pp 317-326.

[6] Bai Hefeng, Michael Savage, Raymond James Knorr: Computer Modeling of Rack–Generating spur gears, *Mechanism and Machine Theory*, Volume 20 no 4, pp 351-360, 1985.

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WORKING PERFORMANCES OF SELF-LUBRICATING SLIDING BEARINGS

Aleksandar MARINKOVIĆ
Ivan SIMONOVIĆ

Abstract: Self-*lubricating* sliding bearings are widely used in numerous industrial applications, primarily regarding their specific lubrication mechanism. This lubrication mechanism is the main advantage compared with classical sliding bearings because their production is not complex and makes lower prices. According to the bearing material and type of exploitation, self-lubricating sliding bearings could operate with oil (grease) in their material structure or even without any amount of lubricant. This paper is dealing with the working performances of this kind of bearings, including their experimental investigation aimed to make a proper choice for a particular Engineering application and corresponding operating conditions.

Keywords: *self-lubricating bearings, working performances, experimental investigation*

1. INTRODUCTION

Most machine and equipment manufacturers are trying to reduce friction loss and make the simplest possible lubrication to settle production costs preserving most machine performances during their working life. According to significant investigations, more than 50% of bearing failures are lubrication related (Figure 1) which makes huge annual losses due to downtime and repairs to equipment damaged by poor lubrication [1].

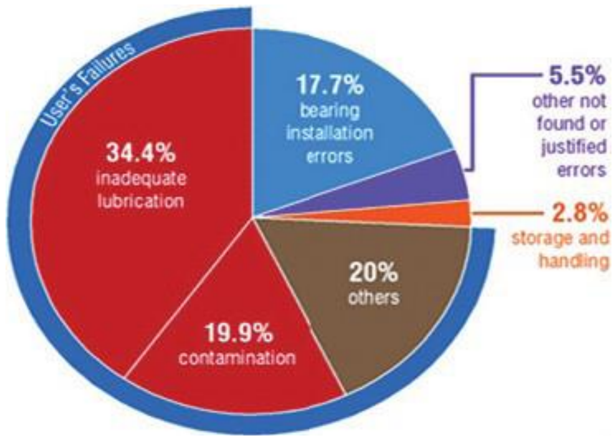

Fig.1.Bearing failures related to tribology performances

There are well-known groups of self-lubricating sliding bearings based on lubrication type, which determines their load capacity such as all other performances relevant for different applications:

- Sliding bearings that work without using any amount of oil or grease. These bearings are made of special plastics, graphite, or some ceramics materials.
- Sliding bearings contain a lubricant, either in special storage or in their material structure. The best known in this group are porous metal bearings made by the sintering process and they are the product of powder metallurgy [2].

2. BEARING PERFORMANCES

The mechanism of the self-lubrication in porous metal bearings improves the lubrication process better, but the coefficient of friction still takes values in a wide interval. That can be understood if we know that bearing life works in regimes from boundary to hydrodynamics lubrication. Lubrication quality and kind of regime are been defined due to all tribology parameters which have an impact on friction and wear process. Besides bearing temperature, quality, and quantity of oil supply, a significant impact has doubtless a coefficient of friction value under particular load capacity and sliding velocity. There are also several common applicated bearing materials, where most physical performances depending on the type of the production, such as bearing-shaft assembly performances, are very important for their use and exploitation in the life cycle.
Those important bearing performances for different most common in use self-lubricating bearing groups of materials were determined by experiments, where an overview from one of the significant manufacturers is presented in *Table 1* [3].

Table 1. Overview of common self-lubricating materials including their main physical performances with limits [3]

	Solid bronze	Sintered bronze	Wrapped bronze	PTFE composite	POM composite
Temperature range, °C	–40 .. +250	–10 .. +90	–40 .. +150	–200 .. +250	–40 .. +110
Friction coefficient, μ	0,08 .. 0,15	0,05 .. 0,10	0,08 .. 0,15	0,03 .. 0,25	0,02 .. 0,20
Permissible load, N/mm^2					
– dynamic	25	10	40	80 ($v \leq 0,02$)	120 ($v \leq 0,02$)
– static	45	20	120	250	250
Permissible sliding velocity, m/s	0,5	0,25 .. 5	1,0	2,0 ($p \leq 1,0$)	2,5 ($p \leq 1,0$)
Shaft tolerance	e7 – e8	f7 – f8	e7 – f8	f7 – h8	h7 – h8
Housing tolerance	H7	H7	H7	H7	H7
Shaft roughness R_a, μm	0 .. 1,0	0,2 .. 0,8	0,4 .. 0,8	0 .. 0,4	0 .. 0,8
Shaft hardness, HB	165 – 400	200 – 300	150 – 400	300 – 600	150 – 600

2.1. Coefficient of friction

Parameters determine the quality of friction in surface contact, define lubrication regime, and at the same time have an influence on the coefficient of friction value. Talking about the influence of constructive parameters on coefficient of friction value, many investigations showed that higher bearing wall thickness decreases the coefficient of friction. The same effect on friction has an increase in bearing length or clearance. The coefficient of friction value also depends on contact surface quality. Because of that great care used to be done in bearing calibration, selection, control, and fine shaft scraping.

Calculated values of Summerfield's number (S) and design variable (ψ) were calculated and placed as points in a diagram that separate areas of hydrodynamics and boundary lubrication [3]. One could observe that lubrication is at least very near hydrodynamic on higher sliding velocity values. On the other side, on lower velocities and higher loads we can talk about boundary lubrication (BL), where lubrication film thickness value is the lowest (Fig. 2).

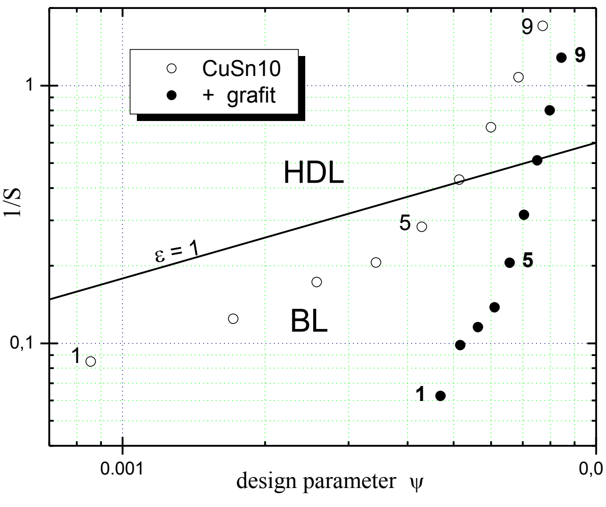

Fig.2. Lubrication regime line with working points

The coefficient of friction based on hydrodynamic lubrication theory in combination with values from already mentioned investigations and calculation of relative oil film thickness could indicate what kind of lubrication we could expect for corresponding working regimes. According to data in Fig.2, one could conclude that during the experimental investigations porous bearings of both materials were mostly working under a regime of boundary lubrication. Just for the highest values of sliding velocity (regimes 8 and 9), where the design parameter approaches higher values, we could talk about mixed lubrication, while under other regimes conditions were far from hydrodynamic lubrication.

2.2. Bearing temperature

By specific sort of bearing such as porous metal bearing, the temperature problem is very important and interesting to analyze with an aim to develop theoretical investigation in this field and so for exploitation of this sort of bearing. The working temperature of the bearing represents the temperature value that becomes constant after some time from start. Friction on the contact surface produces heat which is taken off only through the housing surface because there is a small amount of oil in porous bearing material. That's a reason for higher work temperature values for this sort of bearing in working life.

Working temperature is very important and it represents the temperature value that becomes constant after some time from start. The friction-produced heat is taken off only through the housing surface because there is a small amount of oil, at work temperature too, in a porous material. That is the reason for higher work temperature value for this sort of bearing in working life. The exploitation of this sort of bearing and many experiments show that working temperature becomes constant after a certain time from the start and its change in that time can be approximate with polynomial (1), which going to be explained and completed in a chapter of experimental investigations.

$$T(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 \qquad (1)$$

Also, complex phenomena of nonuniform temperature distribution on sliding bearing volume are very interesting to explore, by analyzing the mathematical model of porous metal bearing, starting from Reynolds differential equation (2) for temperature distribution of isotropic and homogeneous material in cylindrical coordinates:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{1}{r^2}\frac{\partial^2 t}{\partial \theta^2} + \frac{\partial^2 t}{\partial z^2} = 0 \qquad (2)$$

On the inside surface of the bearing, we have boundary conditions of the second sort, while thermal flux produces heat in the shaft-bearing system. Boundary conditions of the third sort are on outside (noncylindrical) surfaces of the bearing, while we have an environmental temperature (T_0) and relation for heat exchange between the surface of bearing and outside air (3):

$$\dot{q}_A = \pm k \left[T_2 - T_0 \right] \qquad (3)$$

The Chapter on experimental investigations going to present also several results of temperature problem investigations on porous metal bearing samples, covering above mentioned theoretical basics.

2.3. Bearing load capacity

Possible the most important performance of sliding bearing for selection crucial for their exploitation is bearing operating range, known as "*PV*-characteristics".
In the relevant literature, there are a few different methods to determine the limiting value of the *PV* range, but three of them are the most common (Fig 4).

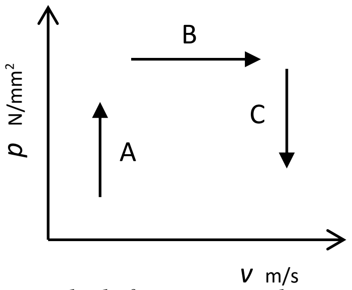

Fig.4. Methods for PV range determination

Method A means rising bearing load at the same velocity, B same load with rising speed, or method C, where the load is reducing on the same applied bearing operating speed.
This performance defines its bearing load capacity determined by experiments. It is a crucial parameter in the aim to make a proper choice of sliding bearing for the particular application. This characteristic shows operating ranges for sliding bearing, which means limits of bearing load *p* in correlation with operating sliding speed *v*.
Authors have numerous results of operating range achieved by own experimental investigations, where only some of them will be presented and explained under the experimental investigations chapter in this paper.
It is also possible to find a lot of data for operating range, those are results published in catalogs from bearing manufacturers as shown example in Fig. 5, for PTFE composite bearing material [4].

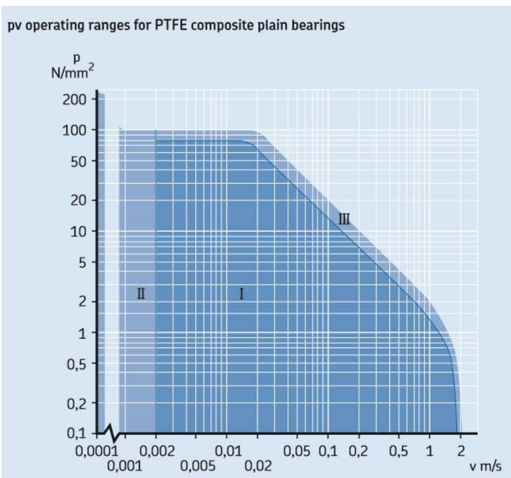

Fig.5. Bearing operating range for PTFE

3. EXPERIMENTAL INVESTIGATION

The expansion of technology, electronics, and home appliances has led to the mass use of sliding bearings primarily due to the positive properties related to shock absorption, overload, and less noise in operation. The experiments were performed to validate numerous theoretical research, test the properties of the bearing, and give guidelines to the exploitation and maintenance. Improvement of the properties of the tested sliding bearing is primarily dealing with their tribological characteristics. A complete performance overview could be obtained by combining experimental results with experiences from exploitation.

3.1. Test devices for experiments

Experimental investigations of sliding bearings used to be conducted into three different groups, up to the purpose:
- Experimental study of mechanical and tribological characteristics for just bearing materials;
- Investigation of oil or grease behavior for the bearing lubrication aimed to improve their operating;
- Experimental study of sliding bearing working performances.

The authors of this paper are presenting results, just a part of experimental investigations dealing with the study of above mentioned bearing working performances.
Depending on the methodology of the experiment, devices are used that observe direct contact between the surfaces of the shaft sleeve and the bearing, devices that simply simulate the operating conditions in which the bearing will work and can be tested in the working environment, ie directly on the machine where it is installed. The choice of testing device depends on the technical conditions and the possibility of using the obtained data. The basic idea is to measure the value of the coefficient of friction over the magnitude of the sliding friction moments on the contact surface of the shaft sleeves and the bearing. The radial load is entered via the loaders of various levers with a fixed-length ratio of 1:10. Applying such a loading system, only constant loads can be set, ie. testing is performed in static conditions during the exploitation (Fig. 6). This type of load is most suitable for real working conditions, especially for self-lubricating sliding bearings.

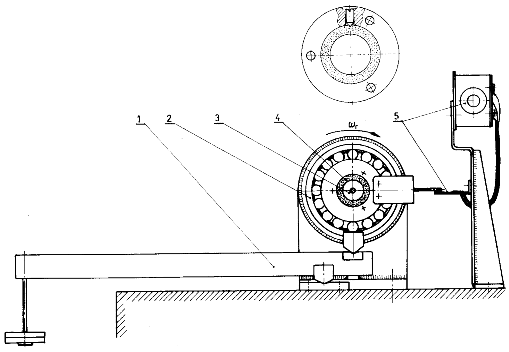

Fig.6. Application load system for sliding bearing

This testing machine is located in Laboratory for Machine elements at Department for Machine Design, belongs to Mechanical Engineering Faculty at the University of Belgrade, and is permanently in use for teaching and research purpose. The machine is powered by an electric motor of P = 1.1kW with a maximum speed of n=2770min^{-1}. Desired rotation speed for bearing can be changed continuously via the AEG frequency regulator, which allows variation of sliding speeds, depending on a different kind of research but also for more precise setting and control of the set speed during the experiments.
Test rig for this investigation used for testing sliding self-lubricating bearings USL 5-30 (*Fig.7.*) was developed in cooperation with Sinter doo company from Užice in mid-Serbia.

Fig.7. Test rig USL 5-30 in laboratory

Using this test rig system for experiments it is possible to apply a portable NI DAQ system [5]. The main reason for DAQ applying in this measurement is the need to continue following two channels for friction torque by DNS and bearing temperature simultaneously. Even not necessary to have a high sample rate for this kind of experiment, the advantages of getting results and its disposal for further analyses are evident (*Fig. 8*).

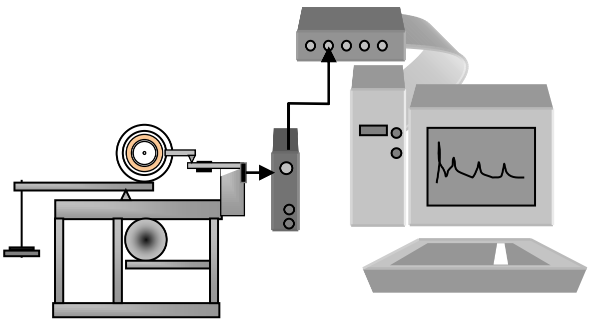

Fig.8. DAQ system for experimental investigations

3.2. Bearing samples

Here are presented just a part of experimental investigations attended to study sliding bearing working performances [6]. Samples for testing, made in sintered Bronze have dimensions Φ20/Φ30×20mm, as a common dimension for some household and agriculture machines purposes. (Fig. 9.).

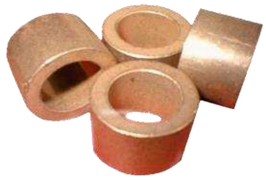

Fig.9. Samples of porous metal bearing made in Bronze

The bearing manufacturer was the same as for the testing machine Sinter doo company, porous metal bearing samples made in sintered bronze (CuSn10). Before testing realization, complete physical and metallographic analysis and sample selection have been conducted. Obtained physical characteristics for this porous metal-bearing material are shown in *Table 2*.

Table 2. Physical characteristics of bearing samples

Material	unit	CuSn10
density	g/cm^3	6,4.......6,5
open porosity	%	22,45.......23,17
radial fracture force	F	3500.......3600
hardness	HB	33,26.......36,24

All selected and measured bearings are controlled and mounted, where shaft/bearing mounting clearance takes value (18...21)μm. During the introduction phase of every experimental investigation, samples were worked out for a couple of hours, just to be prepared aim to simulate real exploitation conditions. Experiments are been conducted under the common external environmental conditions in the Laboratory, which means a temperature of about 20±3^{0}C and the air humidity range (40…70)%.

3.3. Selected results of experiments

The dependence of temperature upon a time has been followed on the working regime with parameters: the radial load of F = 170 N and rotation speed of n = 4780 rpm (for boundary value of PV characteristics) [6]. Temperature values were measured every 2,5 minutes from the start until these parameters become constant and the result of this measurement is shown in *Fig. 10*.

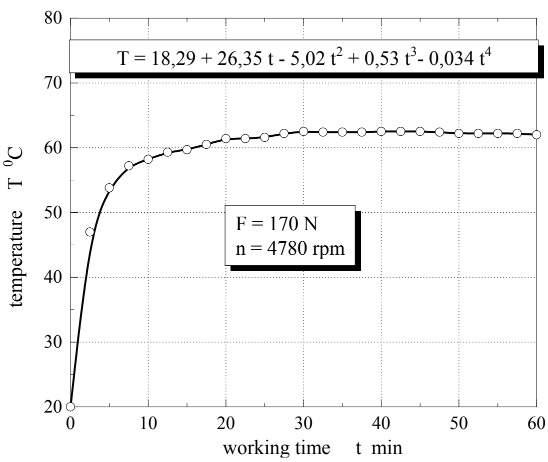

Fig.10. Bearing temperature due to working time

The temperature distribution on bearing volume has been done on working regime determinate with radial load F = 550 N and rotation speed of n = 1350 rpm. In eight different points outside around the bearing are measured temperature values, analogously tester (Fig.11).

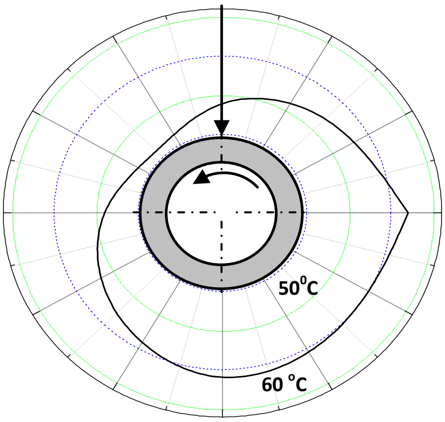

Fig.11. Temperature distribution on bearing volume

Investigation results, made on different operating conditions show that the maximum measured value of operating temperature was T = (76...84)^{o}C. The coefficient of friction values, measured at start of operating, were μ_o = (0,135...0,180), and the values of stationary friction coefficient were μ = (0,029...0,060).
The experimental investigation aimed to determine the bearing PV operating range for selected material and sample dimensions is conducted using method A (shown in *Fig.4*). Results of those experiments could be presented in form of *Table 3*. where limiting values of load and sliding speed are grouped in five working regimes.

Table 3. Results of pv - range determination

regime no.	*v*, m/s	W, N	*p*, N/mm^2	*pv*, W/mm^2
1	1,25	1400	3,5	4,375
2	2,0	900	2,25	4,50
3	3,0	500	1,25	3,75
4	4,0	300	0,75	3,0
5	5,0	210	0,525	2,625

Based on those results it is possible to present a diagram of the limiting PV operating range for this kind of bearing and explained material, with five selected working regimes represented with points in the PV diagram shown in *Fig. 12*. Observing all presented experimental results, those mostly were focused on porous metal bearings, where the lubricant is in material volume. But current trends in new ecological and low energy efficiency bearings lead us to think in direction of using new trends in polymer-based or different composite materials for particular bearing applications. Current and future studies of those bearing materials are conducted aimed to compare them with porous metal bearings and find possible advantages in the particular industry use. Regarding their advantages, plastic bearings are a good solution for many applications in machinery that require a clean and oil-free operation, corrosion resistance, high damping characteristics for vibrations, ability to reliably work under static or dynamic loads in dry conditions [8].

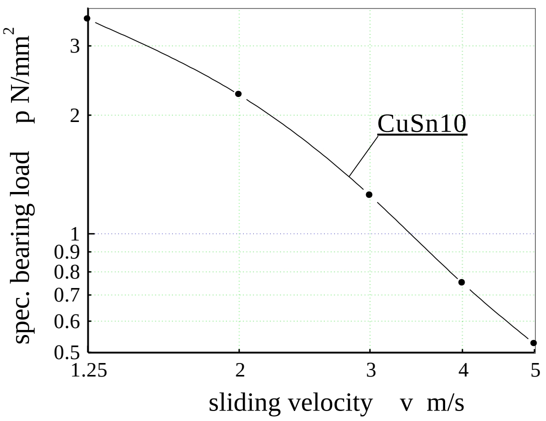

Fig.12. PV operating range due to regime points

Sliding bearings made of composite materials with polymer matrix, which are also subject to our research last years, belong to the group of self-lubricating bearings operating without oil or grease. There is a filler added to the base material whose purpose is to reduce the coefficient of friction of the base material and therefore to eliminate the need for additional lubrication. PTFE-based composite bearing, with the cross-section shown in *Fig 13*. are dry bearings designed to operate without lubricant and it is particularly suitable for high loads and medium speed applications. Its operating temperature is up to 250 °C and the best using sliding velocity is up to 2 m/s. Some typical applications of these bearings are in the automotive industry, materials handling equipment, home appliances, consumer goods, textile machinery, etc. On another side, in the same group is the POM composite sliding bearing, specially designed to operate with boundary lubrication. This kind of bearing requires only a trace of lubricant to operate satisfactorily for long periods, so they are considered pre-lubricated bearings. The sliding surface has a highly effective grease retention system with lubrication pockets, which serve as "lubricant reservoirs". This POM Composite consists of three bonded layers: a copper-plated steel backing strip and a sintered porous tin bronze matrix covered with acetyl (POM), *Fig 13*.

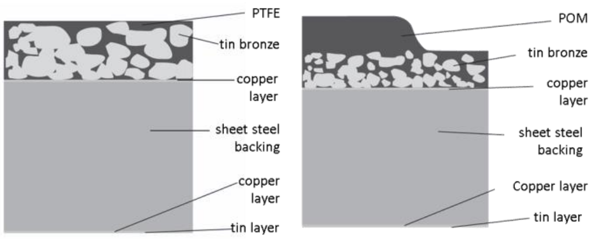

Fig.13. Cross-section of PTFE and POM composites

Several investigations conducted last year were subjected to composite bearing research, using the same equipment for experimental investigations, in Laboratory for Machine Design at Mechanical Engineering Faculty, University of Belgrade. Experiments with this group of bearings aim to get more results that are going to designers easier to select the exact self-lubricating bearing which fits the best for a particular industrial application [9]. Dimensions of examined composite bearing samples are selected due to a possibility of comparison with properties of porous metal bearings and taking into account constructive performances of the own test rig used for experiments. Examined selected samples for testing have dimensions of ∅20 / ∅23 × 20mm, as a common size for some of their typical applications. In combination with shafts made of steel 16MnCr5 (Hardness: 60 HRC), loose fit in the shaft-bearing interface was defined by ∅20 H7/f7, where an operating clearance in testing belongs to the range 20-62 μm. Similar trends in results of operating performance investigations with this kind of bearings give us practical guidelines, that could be very useful in comparison with other bearings, which is partly mentioned in the conclusion chapter.

4. CONCLUSION

Investigations presented in this paper show that the temperature of porous metal bearing becomes constant after (30...50) minutes from the working start and its dependence on time can be the best polynomial approximate (*Fig.10*). The results presented in this paper also show that temperature distribution around porous metal bearing (*Fig.11*), made by experiments This distribution is very similar to the pressure distribution given by hydrodynamic lubrication theory. That means that maximum temperature values are in the area near load and rotating direction and for a minimum situation is the opposite. Comparing those experimental results with the numerical solution of bearing temperature distribution are in progress and going to be published soon in papers and Conferences. Friction coefficient measured at start of testing were μ_O=(0,135...0,180), but the values of stationary friction coefficient have significant lower values μ = (0,029...0,060).

Similar trends and results are observed in experiments with composite bearings, where both temperature and coefficient of friction values of tested bearing become constant till 1 hour of operating, and their dependence from time could be polynomial approximate.

Presented results overview with bearing study represent an introduction in further researches of plastic bearings subjected to make simpler machine maintenance and better energy efficiency. Great expansion and clearly explained advantages of polymer and composite bearings application in several branches of industry, encourage us not only in the investigation of new materials but also for new qualitative bearing behavior analysis in dry, maintenance-free conditions under different lubricants during exploitation life.

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REFERENCES

[1] Mat Mowry: *The True Cost of Bearing Lubrication*, igus White Paper, igus®inc.USA, 2012.

[2] Cheng J.A., Lawley A., Smith W.E., Robertson J.M., *Structure property and performance relations in self-lubricating bronze bearings: commercial premixes*, The International Journal of Powder Metallurgy, vol.22, No.3., 1986.

[3] Kameron, A., Morgan, T.V., Stainsby, E.A.: "Critical Conditions of Hydrodynamic Lubrication of Porous Metal Bearings", Proc. Inst. Mech. Engs., 1960, vol.176, No.2, 761-770.

[4] SKF *Bushings and plain bearings, Compact and maintenance-free*, SKF Group, 2012.

[5] Marinković A., Vencl A., Wallace P. (2007) *Portable* DAQ *equipment with LabVIEW as a tool for tribology experiments and condition monitoring*, Proceedings of 10th International Conference on Tribology Serbiatrib '07, Kragujevac, pp.105-108.

[6] Janković M., *The investigation of porosity influence on porous metal bearings working performances*, Ph.D. thesis, Faculty of Mechanical Engineering, Belgrade 1988.

[7] Marinkovic A., Lazovic T., Stankovic M. (2012) *Experimental Investigation of Porous Metal Bearings*, Proceedings of the 15th International Conference on Experimental Mechanics – ICEM15, pp.2718/1-2718/6, Porto, Portugal.

[8] Marinković A. Stanković M., *Advantages and Applications of Self-Lubricating Plastic Bearings*, Proceedings of International Conference in Tribology, Serbiatrib 2013, pp.135–140., 2013.

[9] Stankovic M., Marinkovic A.: *Tribological Properties of Selflubricating Sliding Bearings Made of PTFE and POM-Based Composite Materials*, Proceedings of the 14th International Conference on Tribology – SERBIATRIB '15, pp.314-318, Belgrade, 2015.

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FAULT DIAGNOSIS OF ROLLING BEARING UNDER VARIABLE OPERATING CONDITIONS BASED ON DEEP LEARNING

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Abstract: *Rolling bearings are commonly used in automotive, machinery, aviation, and wind turbine fields due to low power consumption, high interchangeability, and high transmission efficiency. Fatigue, elevated temperature, contamination, etc., can cause damage to the bearings, and this may lead to unscheduled shutdowns and significant economic losses or even human casualties. From this standpoint, timely and accurate monitoring and diagnosis of bearing faults is essential to assure the safe and reliable operation of industrial systems. The industry has become more data-driven with the wide availability of sensors and ever-increasing computation power. In this regard, deep learning (DL) is increasingly popular due to its ability to capture sensitive fault information without expert knowledge. This paper deals with a bearing fault diagnosis method based on DL by utilizing vibration data. A multi-class classification problem was solved by examining variable working conditions (i.e., shaft speed and loads) and three health classes. The performance of the developed DL-based approach was evaluated through prominent benchmark datasets: (i) Case Western Reserve University and (ii) Paderborn University datasets. The results indicate that the proposed DL-based method was suitable for identifying different bearing faults under variable operating conditions and can optimize maintenance costs by early fault detection.*

Keywords: *rolling bearing; condition monitoring; deep learning; fault diagnosis; vibration*

1. INTRODUCTION

With the upgrading of industrial capacity, the relationship between mechanical equipment has become increasingly inseparable [1]. An unexpected failure in a machine can indirectly affect the reliability of other linked mechanical equipment [2]. To ensure a safe and orderly operation, the rotating machinery plays an irreplaceable role in industrial production. In this regard, the rolling-element bearings are considered a vital component of rotating machinery as they reduce friction between the different elements, take the load, and support the shaft [3, 4]. Their health condition is also essential for the safe operation and thus uninterrupted availability of mechanical systems. However, bearings are among the most error-prone machine elements in modern industry. For example, approximately 45-55% of rotary machinery failures are due to rolling bearing errors [5]. A lack of prompt and accurate diagnosis of bearing faults may lead to financial loss and severe health risks [6]. To manage the potential failure of mechanical systems, the automatic and timely monitoring of rolling-element bearing faults is essential.

In the current industrial era called "Industry 4.0," the manufacturers are increasingly relying on data collected through the sensors altogether with the boosted computation power [4]. The sensor data collected from an industrial system may be, for example, vibration, motor current, thermal image, or acoustic data. Among them, the vibration data are frequently utilized to achieve diagnostics tasks due to its advantages, for instance, low cost and rapid measurement [7]. Diagnosis of rolling bearing faults is generally based on data-driven approaches. In general, three main steps are defined with regard to traditional intelligent fault diagnosis methods: (1) data acquisition, (2) feature extraction and selection, and (3) pattern recognition/fault classification [8, 9]. Following this, two crucial shortcomings arise. First, advanced signal processing knowledge is required for feature extraction due to vibration signals' nonlinear and non-stationary nature. Second is the necessity to extract many features in different domains to reflect the bearing characteristics [5-10]. To apply classical data-driven techniques, the feature extraction and selection processes need prior expertise and knowledge; this is a labour-oriented task. Vibration signals collected from industrial systems are often exposed to background noises that do not contain information regarding fault [11]. In this regard, it is hard for shallow structures to learn complicated nonlinear relationships [12]. As a result, there is an urgent necessity to develop new intelligent techniques that can automatically achieve rolling-element bearing fault diagnosis tasks.

As an emerging research field, Deep Learning (DL) is increasingly popular due to its ability to capture sensitive fault information without expert knowledge. In this regard, DL is a powerful tool in order to extract the representative features from the sensor data [1, 13]. One of the significant contributions of DL is that it can automatically learn discriminative features to classify faults and eliminates the necessity of prior knowledge (i.e., human involvement) required for manual feature extraction. He et al. [1] endeavoured to develop an intelligent diagnosis approach based on ensemble sparse auto-encoders, considering the shortcomings of traditional methods. The study utilized the Case Western Reserve University (CWRU) dataset to assess the proposed method's performance. In addition, the robustness of the developed DL method was evaluated against different background noises. Later, Chen et al. [3] proposed a deep transfer Convolutional Neural Network (CNN) to classify various rolling bearing faults. The study converted the raw vibration data into time-frequency images to achieve this end. Two experimental datasets (i.e., CWRU and centrifugal pump test rigs) were employed to validate the proposed method; consequently, an overall classification accuracy of near 100% was achieved. To diagnose different bearing faults, Liu et al. [8] developed a new DL-based method, namely, hierarchical multitask CNN. Their study benefited from the experimental dataset collected through the test setup of Paderborn University (PU) in Germany. As a result, the proposed hierarchical multitask CNN method showed superior performance against other methods considered within the scope of the research work. Shao et al. [9] proposed a bearing fault diagnosis method, namely, deep ensemble auto-encoders. The developed method was utilized to analyse vibration signals collected through the CWRU test setup. It was revealed that the proposed method could remove the dependency on manual feature extraction. Karpat et al. [10] developed a six-degrees-of-freedom dynamic model of a single-stage gearbox and collected simulated vibration data for healthy and cracked involute spur gears. Their study developed a 1D CNN architecture to classify different crack degrees, considering diverse tooth profiles. As a result, an overall classification accuracy of 93.07% was obtained.

Rolling bearings are commonly used in diverse industrial systems owing to low power consumption, high interchangeability, and high transmission efficiency. A fault can develop in bearings due to variable operating conditions, elevated temperature, insufficient lubrication, or fatigue [14]. The recognition accuracy of artificial intelligence algorithms may reduce due to variable operation conditions (e.g., shaft speed and loads), resulting in misclassification [5, 15]. Hence, the influence of different shaft speeds and loads on the prediction accuracy of DL-based methods needs to be well-addressed. To detect various bearing faults (outer raceway and combined defects), Tayyab et al. [4] proposed an approach based on CNN and order maps. The prediction accuracy of the proposed method was compared with the performances of other algorithms in the literature, considering variable shaft speeds and loads. Karpat et al. [5] developed a 1D CNN structure and classified different bearing faults (i.e., inner and outer raceway faults), considering multiple shaft speeds and loads. Their study benefited from the PU experimental dataset to validate the proposed method. Consequently, an overall classification accuracy of 93.97% was obtained. Rostaghi et al. [6] proposed a DL-based approach and considered three different fault types (rolling element, inner and outer raceway) and shaft speeds (1730, 1750, and 1772 RPM). CWRU dataset was employed in order to achieve diagnostics tasks. Hao et al. [12] developed an intelligent diagnosis method based on deep residual networks. The effectiveness of the method was evaluated through the CWRU experimental dataset. The research concluded that the prediction accuracy could be improved up to 99.83%, utilizing the developed method. Sabir et al. [16] used the long-short term memory algorithm to classify various rolling bearing faults. They employed the PU dataset and considered variable shaft speeds, radial forces, and torques. As a result, the proposed method performed fault classification with an overall accuracy of nearly 96%.

This paper developed a 1D CNN structure to classify different rolling bearing faults under variable operating conditions (i.e., shaft speeds and loads). To this end, a multi-class classification problem was solved in the presence of rolling elements and inner and outer raceway faults. The performance of the developed DL-based approach was evaluated through prominent benchmark datasets: (i) CWRU and (ii) PU datasets. As a result, the proposed 1D CNN method classified different bearing faults with an overall accuracy of 99.37% and 96.67% with regard to datasets, respectively. The findings indicate that the proposed DL-based method was suitable for identifying different bearing faults under variable operating conditions and can optimize maintenance costs by early fault detection.

2. MATERIAL AND METHOD

This section addresses the typical bearing structure and fault signature of rolling-element bearings, details of employed benchmark (i.e., CWRU and PU) datasets, and the structure of the developed 1D CNN method, respectively.

Fig. 1 depicts a representative image of a rolling-element bearing layout that includes outer and inner raceways, rolling elements, and the cage that holds these elements. As above-discussed, bearings are among the most significant and useful machine elements used in rotating machinery. Their health status also affects mechanical systems' safety, reliability, and overall performance [12]. In real-life scenarios, a malfunction may occur to rolling-element bearings due to the harsh operating conditions, incorrect size selection, wear, etc. [5, 14]. Bearings' vibration signals generally exhibit a nonlinear behavior due to the friction, nonlinear and coupling interactions, and stiffness [6]. Further, the signal complexity is affected by faults at various signal scales. Altogether, the sensor data collected from an industrial system starts to produce abnormal system responses whose magnitudes rely on fault type, size, and location in the presence of a fault.

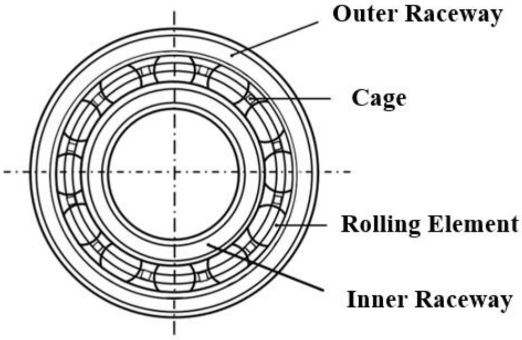


Fig.1. Typical rolling bearing structure

The time-frequency characteristics of the faults may also differ according to the fault degree and orientation [17]. Early diagnosis of faults in mechanical systems operating under variable working conditions (e.g., shaft speeds and loads) is critical where high reliability is required, such as in the aviation and wind turbine fields. Otherwise, many losses are inevitable, from finance to human casualties. In this regard, DL-based approaches have gained a lot of attention over the past decade due to their ability to capture sensitive fault information without expert knowledge.

2.1. Experimental setups

The present study employed CWRU and PU datasets to evaluate the performance of the developed DL-based method [18, 19]. The sub-section will explain the details of two prominent benchmark datasets as well as the health statuses (i.e., classes) and operating conditions (i.e., shaft speeds and loads) considered within the scope of the research work.

First, the CWRU bearing test rig consists of a 2 HP electric motor, a torque transducer/encoder, and the load (i.e., dynamometer) [18]. Different single-point faults (from 0.007 to 0.040 inches in diameter) were introduced with Electro-Discharge Machining (EDM) to the 6205-2RS SKF test bearings supporting the motor shaft. Faulty bearings were then remounted on the test motor, and vibration data were collected through the accelerometers attached to the housing. The test setup was run under four different shaft speeds (from 1797 to 1720 RPM) and loads (from 0 to 3 HP). The schematic diagram of the CWRU experimental test rig is illustrated in Fig. 2.

The present study selected 6 cases from the CWRU dataset and evaluated the proposed 1D CNN model's performance under variable shaft speeds and loads. To this end, three health conditions (i.e., healthy, inner raceway, and rolling element faults) were considered, and the robustness of the DL-based was assessed under variable working conditions (1 HP and 1772 rpm, and 2 HP and 1750 rpm). Further, the faults introduced at 0.014 inches (i.e., approximately 0.36 mm) in diameter were used in the present study. The operating conditions of test bearings and the classes identified are detailed in Table 1.

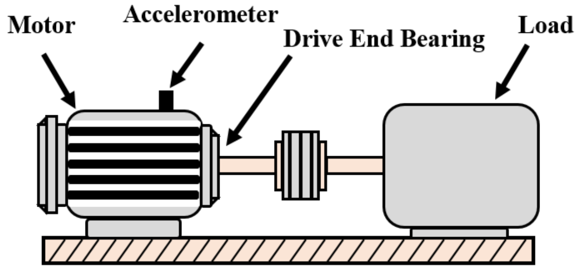


Fig.2. Experimental setup of CWRU

Table 1. Operation conditions of test bearings (CWRU)

Fault Type	Load (HP)	Speed (RPM)	Label
Healthy	1	1772	H_1
Healthy	2	1750	H_2
Inner Raceway	1	1772	F_1
Inner Raceway	2	1750	F_2
Rolling Element	1	1772	F_3
Rolling Element	2	1750	F_4

Second, the PU bearing test rig consists of a test motor, a measuring shaft, a bearing module, a flywheel, and a load motor [19]. The dataset includes 32 vibration signals (i.e., healthy, artificially damaged, and accelerated lifetime tests) for three health conditions (i.e., healthy, inner, and outer raceway faults). Artificial damages are introduced to the 6203 grooved ball bearings in three ways: (1) EDM, (2) electric engraver machine, and (3) drilling. The schematic diagram of the PU experimental test rig is depicted in Fig. 3.

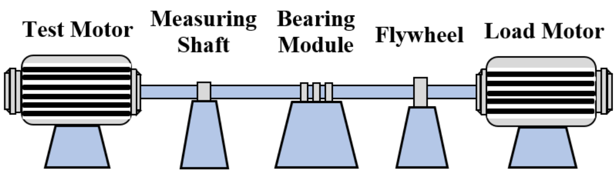


Fig.3. Experimental setup of PU

The present study selected 6 cases from the PU dataset to assess the proposed DL-based method's performance under variable load torques (0.1 and 0.7 Nm). To this end, the signals collected due to artificial damages introduced by EDM (trench of 0.25 mm length in rolling direction and depth of 1-2 mm) were given as input data to the 1D CNN algorithm, considering three health conditions (i.e., healthy, inner, and outer raceway faults). To examine the influence of load torques, the shaft speed was kept constant at 1500 RPM, and the radial force at 1000 N.

The operating conditions of test bearings and the classes identified are detailed in Table 2.

Table 2. Operation condition of test bearings (PU)

Fault Type	Torque (Nm)	Shaft Speed (RPM)	Label
Healthy	0.7	1500	N_1
Healthy	0.1	1500	N_2
Inner Raceway	0.7	1500	IR_1
Inner Raceway	0.1	1500	IR_2
Outer Raceway	0.7	1500	OR_1
Outer Raceway	0.1	1500	OR_1

2.2. Convolutional neural network

CNN is a feed-forward multi-stage neural network that mainly contains three layers, namely, (1) convolution layer, (2) pooling layer, and (3) fully connected layer [8]. The convolution layer is used to extract different features and obtain feature maps. On the other side, the pooling layer is mainly utilized to perform a down-sampling operation [9]. CNN is also one of the most utilized DL methods in order to classifying various rolling-element bearing faults [7, 8].

The present study used 70% of the data for training, 15% for testing, and 15% for validation. The window size was defined as 25000. Dropout is a common method to solve the overfitting problem in DL algorithms [12]. Some neurons are randomly dropped by Dropout to ensure that the neural network only propagates forward during the training iteration. In this regard, the Dropout ratio was set to 0.5 in the present research work. The developed model includes four convolutions and pooling layers. This study used 4 feature maps with kernel size 1 and Rectified Linear Units (ReLu) function as the activation function in the first layer. The output of the first neural network layer is a 25000 x 4 neuron matrix (Table 3). Similar to the first layer, the feature map and the kernel size in the second convolution layer were determined as 4 and 1, respectively. These values (i.e., feature maps and kernel size) were assigned as 8 and 1 for the third and fourth convolution layers. The Hyperbolic Tangent function (tanh) was utilized as the activation function in the second, third, and fourth convolution layers. The Adam (Adaptive Moment Estimation) optimizer was adopted to optimize the network and improve the overfitting problem [12]. The categorical cross-entropy loss function, which has fast convergence speed and strong generalization ability, was used to learn a multi-class classification problem [9]. The structure of the 1D CNN model is indicated in Table 3.

Table 3. The structure of the 1D CNN model

Layer (Type)	Output Shape	Param #
conv1d_8 (Conv1D)	(None, 25000, 4)	8
max_pooling1d_8 (MaxPooling1D)	(None, 12500, 4)	0
conv1d_9 (Conv1D)	(None, 12500, 4)	20
max_pooling1d_9 (MaxPooling1D)	(None, 6250, 4)	0
conv1d_10 (Conv1D)	(None, 6250, 8)	40
max_pooling1d_10 (MaxPooling1D)	(None, 2083, 8)	0
conv1d_11 (Conv1D)	(None, 2083, 8)	72
max_pooling1d_11 (MaxPooling1D)	(None, 694, 8)	0
dropout_2 (Dropout)	(None, 694, 8)	0
flatten_2 (Flatten)	(None, 5552)	0
dense_8 (Dense)	(None, 256)	1421568
dense_9 (Dense)	(None, 128)	32896
dense_10 (Dense)	(None, 64)	8256
dense_11 (Dense)	(None, 6)	390

3. RESULTS AND DISCUSSION

The present study developed a 1D CNN model to classify different rolling-element bearing faults (i.e., healthy, rolling element, inner, and outer raceway faults) and evaluated its recognition ability under variable operating conditions (i.e., shaft speeds and loads). To do so and further extend the scope of implementation, two prominent benchmark datasets were employed: (i) CWRU and (ii) PU datasets [18, 19].

This section details the vibration signals collected through two different experimental setups and performance evaluation of the proposed DL-based method via some well-known performance metrics. The signals collected from the CWRU test rig under variable operating conditions are illustrated in Fig. 4 to 6.

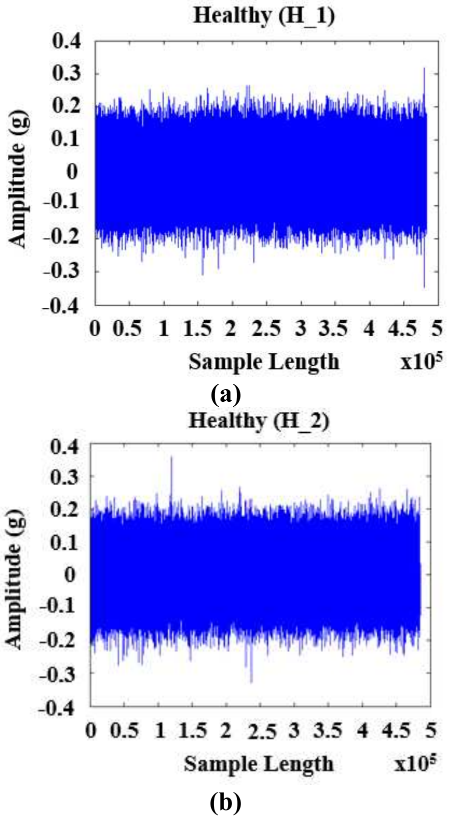


Fig.4. Vibration signals of healthy bearings (a) 1 HP / 1772 RPM and (b) 2 HP / 1750 RPM

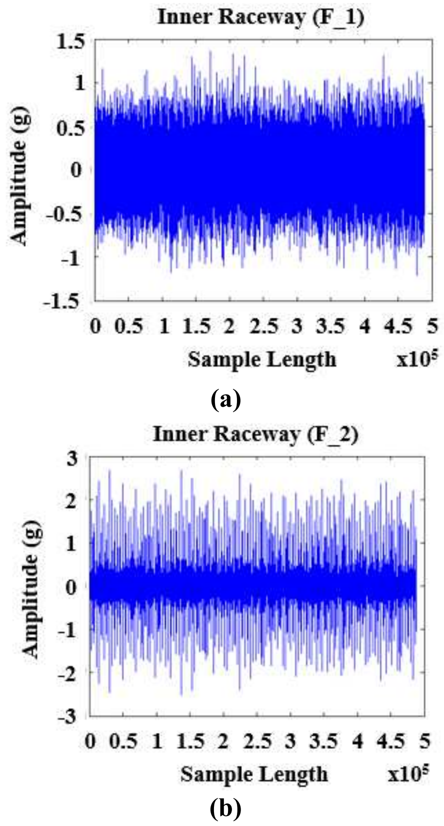


Fig.5. Vibration signals of bearings with inner raceway fault (a) 1 HP / 1772 RPM and (b) 2 HP / 1750 RPM

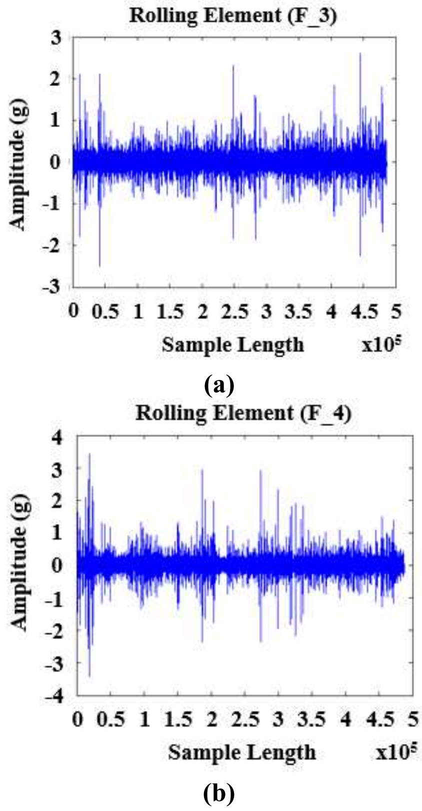


Fig.6. Vibration signals of bearings with rolling element fault (a) 1 HP / 1772 RPM and (b) 2 HP / 1750 RPM

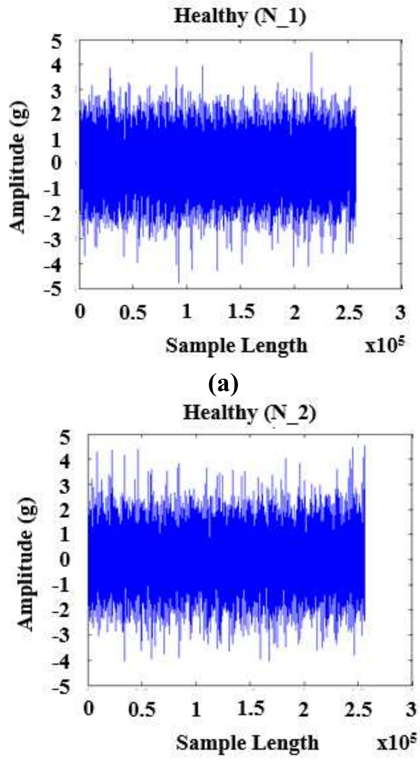
Figs 4 to 6 show that the signals of each case are similar among themselves. As an exception for the inner raceway fault case, the vibration signals collected for motor power of 2 HP (i.e., label F_2) fluctuate more than the data collected for 1 HP (i.e., label F_1). Further, it was observed that the bearings' vibration responses were stronger in faulty conditions than in healthy states.

The present study plotted a confusion matrix to further interpret the results obtained through the CWRU dataset (Fig. 7). It was observed that the proposed 1D CNN classified the healthy state (i.e., H_1 and H_2) and the inner raceway faults (F_1 and F_2) perfectly. With this in mind, Fig. 7 also points out that the model had slightly confused classifying rolling element faults under variable operating conditions. As a result, the average classification accuracy was 99.37%, considering the vibration signals collected through the CWRU dataset.

Actual Label \ Predicted Label	H_1	H_2	F_1	F_2	F_3	F_4
H_1	1.000	0.000	0.000	0.000	0.000	0.000
H_2	0.000	1.000	0.000	0.000	0.000	0.000
F_1	0.000	0.000	1.000	0.000	0.000	0.000
F_2	0.000	0.000	0.000	1.000	0.000	0.006
F_3	0.000	0.000	0.000	0.000	0.996	0.028
F_4	0.000	0.000	0.000	0.000	0.004	0.966

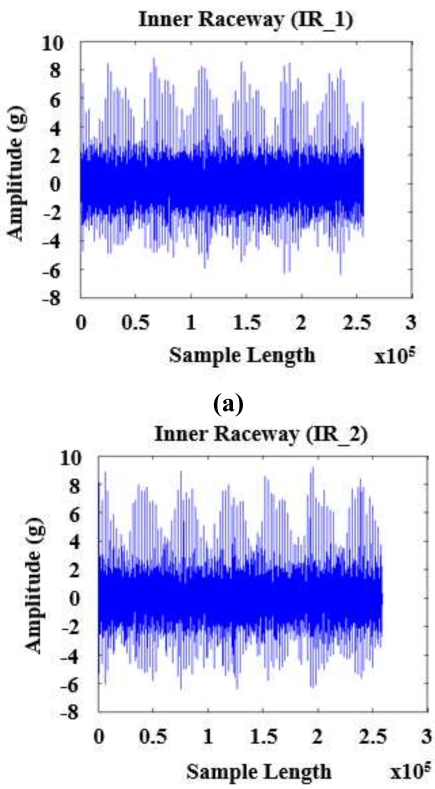
Fig.7. Confusion matrix for CWRU dataset

The process applied for the CWRU dataset was repeated for the PU dataset. In this regard, the signals collected from the PU test rig are illustrated in Fig. 8 to 10.



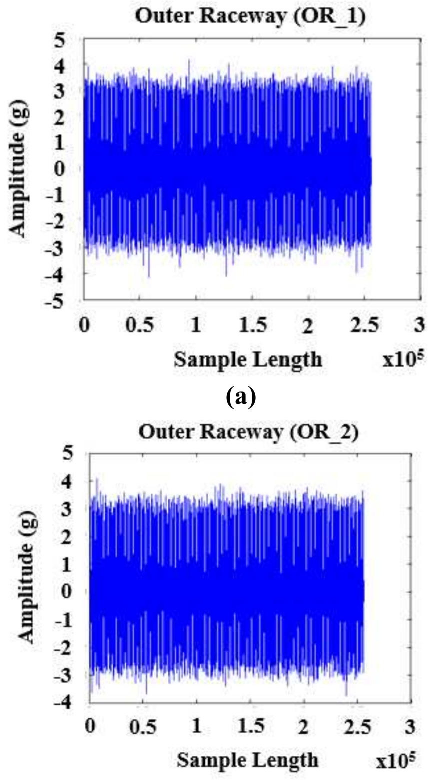
(b)

Fig.8. Vibration signals of healthy bearings (a) 0.7 Nm and (b) 0.1 Nm



(b)

Fig.9. Vibration signals of bearings with inner raceway fault (a) 0.7 Nm and (b) 0.1



(b)

Fig.10. Vibration signals for bearings with outer raceway fault (a) 0.7 Nm and (b) 0.1 Nm

Figs 8 to 10 indicate that the vibration signals were relatively more sensitive to the inner raceway faults than the other health conditions (i.e., healthy and outer raceway faults) considered within the scope of this research work. The present study plotted a confusion matrix to interpret the results obtained through the PU dataset (Fig. 11). It was observed that the proposed 1D CNN classified the healthy state (i.e., N_1 and N_2) and the inner raceway faults (IR_1 and IR_2) perfectly among themselves. Fig. 11 also shows that the model was performed relatively poorly in classifying outer raceway faults under variable load torques (i.e., 0.1 and 0.7 Nm). The average classification accuracy obtained after testing the model with the PU dataset was 96.67%.

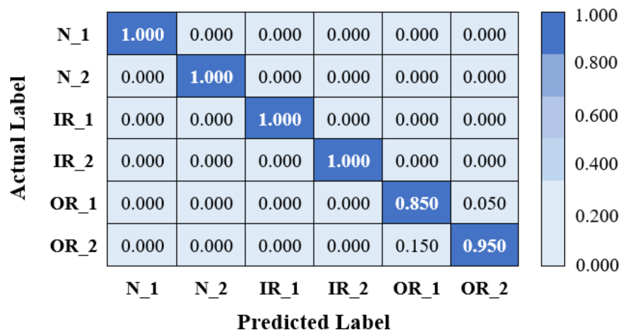


Fig.11. Confusion matrix for PU dataset

The CWRU and PU datasets are commonly utilized for bearing fault diagnostics tasks and are considered a standard reference for model validation purposes [12, 20]. Hao et al. [12] proposed an intelligent diagnosis method and tested their algorithm's efficacy under variable operating conditions. The CWRU benchmark dataset was employed for model validation. Consequently, it was concluded that the proposed "end-to-end" algorithm shortened the training time and showed good versatility. Pandhare et al. [20] benefited from the PU benchmark dataset and assessed the performance of the classical CNN method. The study concluded that the CNN method with time-frequency domain input outperformed the support vector machine and k-nearest neighbour algorithms. Chen et al. [21] evaluated a transferable CNN model's performance, considering variable working conditions. The study tested the fault recognition accuracy of the proposed model through three different experimental test rigs and further concluded that the transferable CNN model was suitable for identifying rotary machinery faults.

To sum up, the rolling bearings are fundamental (but also error-prone) machine elements widely used in many fields, including automotive, wind turbine, machinery, and aviation. Damage to the bearings may develop due to wear, electrical leakage, fatigue, etc. Failure to detect faults early may result in unplanned shutdowns and thus financial loss. This may even cause human casualties, depending on the fault degree and implementation field (e.g., safety-critical applications, such as wind turbines). In the era of big data, DL algorithms enable automatically learning discriminative fault features to classify diverse rotary machinery faults without expert knowledge and capture sensitive fault information. By utilizing DL-based approaches, the maintenance costs can be optimized, and further health risks can be minimized through the early fault diagnosis of rotary machinery faults.

4. CONCLUSION

This paper deals with developing a DL-based approach to diagnosing different bearing faults under variable operating conditions. To this end, the performance of the developed DL-based method was evaluated through benchmark datasets: (i) CWRU and (ii) PU datasets. As a result, the proposed 1D CNN method classified different bearing faults with an overall accuracy of 99.37% and 96.67% regarding datasets, respectively. The results confirm that the proposed 1D CNN method was suitable for identifying bearing faults under variable operating conditions and can optimize maintenance costs by early fault detection.

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REFERENCES

[1] He, J., Ouyang, M., Yong, C., Chen, D., Guo, J., Zhou, Y.: A novel intelligent fault diagnosis method for rolling bearing based on integrated weight strategy features learning. *Sensors (Basel)*, Vol. 20, pp. 1-20, 2020.

[2] Lei, Y., Li, N., Guo, L., Li, N., Yan, T., Lin, J.: Machinery health prognostics: A systematic review from data acquisition to RUL prediction. *Mechanical Systems and Signal Processing*, Vol. 104, pp. 799-834, 2018.

[3] Chen, Z., Cen, J., Xiong, J.: Rolling bearing fault diagnosis using time-frequency analysis and deep transfer convolutional neural network. *IEEE Access*, Vol. 8, pp. 150248-150261, 2020.

[4] Tayyab, S.M., Chatterton, S., Pennacchi, P.: Intelligent defect diagnosis of rolling element bearings under variable operating conditions using convolutional neural network and order maps. *Sensors (Basel)*, Vol. 22, pp. 1-24, 2022.

[5] Karpat, F., Kalay, O.C., Dirik, A.E., Doğan, O., Korcuklu, B., Yüce, C.: Convolutional neural networks based rolling bearing fault classification under variable operating conditions. *Proceedings of IEEE 2021 International Conference on Innovations in Intelligent Systems and Applications*, 25-27 August, Kocaeli, Turkey, pp. 1-6, 2021.

[6] Rostaghi, M., Khatibi, M.M., Ashory, M.R., Azami, H.: Bearing fault diagnosis using refined composite generalized multiscale dispersion entropy-based skewness and variance and multiclass FCM-ANFIS. *Entropy (Basel)*, Vol. 23, pp. 1-17, 2021.

[7] Wang, X., Mao, D., Li, X.: Bearing fault diagnosis based on vibro-acoustic data fusion 1D-CNN network. *Measurement*, Vol. 173, 2021.

[8] Liu, Y.-Z., Zou, Y.-S., Jiang, Y.-L., Yu, H., Ding, G.-F.: A novel method for diagnosis of bearing fault using hierarchical multitasks convolutional neural networks. *Shock and Vibration*, pp. 1-14, 2020.

[9] Shao, H., Jiang, H., Lin, Y., Li, X.: A novel method for intelligent fault diagnosis of rolling bearings using ensemble deep auto-encoders. *Mechanical Systems and Signal Processing*, Vol. 102, pp. 278-297, 2018.

[10] Karpat, F., Dirik, A.E., Kalay, O.C., Yüce, C., Doğan, O., Korcuklu, B.: Fault diagnosis with deep learning for standard and asymmetric involute spur gears. *Proceedings of 2021 ASME International Mechanical Engineering Congress and Exposition*, 1-5 November, Virtual, Online, 2021.

[11] Mousavi, Z., Ettefagh, M.M., Sadeghi, M.H., Razavi, S.N.: Developing deep neural network for damage detection of beam-like structures using dynamic response based on FE model and real healthy state. *Applied Acoustics*, Vol. 168, 2020.

[12] Hao, X., Zheng, Y., Lu, L., Pan, H.: Research on intelligent fault diagnosis of rolling bearing based on improved deep residual network. *Applied Sciences*, Vol. 11, pp. 1-14, 2021.

[13] Yüce, C., Gecgel, O., Doğan, O., Dabetwar, S., Yanik, Y., Kalay, O.C., Karpat, E., Karpat, F., Ekwaro-Osire, S.: Prognostics and health management of wind energy infrastructure systems. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, Vol. 8, pp. 1-18, 2022.

[14] Hou, L., Jiang, R., Tan, Y., Zhang, J.: Input feature mappings-based deep residual networks for fault diagnosis of rolling element bearing with complicated dataset. *IEEE Access*, pp. 180967-180976, 2020.

[15] Wang, S., Wang, D., Kong, D., Wang, J., Li, W., Zhou, S.: Few-shot rolling bearing fault diagnosis with metric-based meta learning. *Sensors (Basel)*, Vol. 20, pp. 1-15, 2020.
[16] Sabir, R., Rosato, D., Hartmann, S., Gühmann, C.: LSTM based bearing fault diagnosis of electrical machines using motor current signal. *Proceedings of 2019 18th IEEE International Conference on Machine Learning and Applications*, 16-19 December, Florida, USA, 2019.
[17] Chen, X., Zhang, B., Gao, D.: Bearing fault diagnosis base on multi-scale CNN and LSTM model, *Journal of Intelligent Manufacturing*, Vol. 32, pp. 971-987, 2021.
[18] https://csegroups.case.edu/bearingdatacenter - Case Western Reserve University, Bearing Data Center, Accessed on: 2022-04-25.
[19] https://mb.uni-paderborn.de/kat/forschung/datacenter - Paderborn University, Bearing Data Center, Accessed on: 2022-04-25.
[20] Pandhare, V., Singh, J., Lee, J. Convolutional neural network based rolling-element bearing fault diagnosis for naturally occurring and progressing defects using time-frequency domain features, *Proceedings of 2019 Prognostics and System Health Management Conference*, 2-5 May, Paris, France, 2019.
[21] Chen, Z., Gryllias, K., Li, W.: Intelligent fault diagnosis for rotary machinery using transferable convolutional neural network, *IEEE Transactions on Industrial Informatics*, Vol. 16, pp. 339-349, 2020.

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CONTACT STRESS AND DEFORMATIONS IN ECCENTRICALLY LOADED THRUST BALL BEARING

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Abstract: *Contact stress and deformations in the thrust ball bearing with a contact angle of 90 ° are considered in this paper. Ideally, an external axial load of this kind of bearings should be centric, but in reality, this force may act eccentrically. As a result, the load distribution between balls is inequal. The most unfavourable case is when the axial force intersects the radius vector of one of the balls. The load, contact stress and contact deformation of this ball are greater than the load of all rest of the balls and greater in the case of equal load distribution. It limits the load-carrying capacity of a real bearing, compared to the theoretical static load rating. Analyzes have shown that considered thrust ball bearings do not lose operational ability at low speeds, even if there is some load eccentricity when an external axial load is not more than 30- 40% of static bearing capacity. Otherwise, additional bearing capacity analyzes are required.*

Keywords: *thrust ball bearing, load distribution, contact deformations, contact stress*

1. INTRODUCTION

The thrust ball bearings can only withstand a pure axial load. Thereby single-row deep groove ball bearings of series 511, 512, 513 and 514, consisting of one row of balls and two washers - shaft washer and housing washer, transmit axial load in one direction.

The rotation speed of thrust ball bearings is limited, because at higher angular velocities, due to centrifugal force, the friction between the balls and the cage increases [1]. That is why these bearings are used in power transmissions, which transmit high torques at low speeds. They are also used in bearing arrangements of rotary cranes and crane hooks, in various types of rotary stands and rotary table feeders, generally for supporting vertical shafts. These bearings do not withstand radial loads. If a radial load component acts in the support, a radial bearing should be mounted together with an axial bearing in the bearing arrangement.

Ideally, the thrust ball bearing should be subjected to a centric load. This means that the direction of the axial force coincides with the bearing axis. Then the load distribution between rolling elements is equal, ie. all balls transfer the same part of the external axial load. However, very often in practice, for various reasons, the external load direction is shifted from the bearing axis by some value, called eccentricity. The reasons for eccentricity could be low manufacturing accuracy of the shaft and the housing, as well as improper installation.

The load distribution between rolling elements of the eccentrically loaded thrust ball bearing is unequal, and the degree of inequality depends on the eccentricity.

Eccentrically loaded ball bearing, as an issue recognized in practice, is also considered in the theory of rolling bearings [2]. The load distribution of an eccentrically loaded thrust ball bearing is mathematically described using Rumbarger integrals [2,3]. This is a well-known methodology applied in the conventional theory of load distribution between rolling elements of thrust ball bearings. However, although there is a mathematical model of load distribution in the thrust ball bearing, which takes into account the eccentricity, the standard recommendations for the calculation of thrust ball bearing's static load rating [4], as well as dynamic load rating and rating life [5] are not included. In these relevant and official documents, which are adhered to by bearing manufacturers, designers, end-users and university literature, the load ratings and rating life of thrust ball bearings are considered under the assumption of centric axial load. Also, a centric axial load is assumed in papers dealing with other types of thrust bearings, as well as with other phenomena (tribological, energy losses, etc.), [6-11]. In the case of eccentrically loaded thrust ball bearing, the accurate mathematical description of the load distribution is important for obtaining the exact load of every single rolling element in the bearing. Then load carrying capacity, as well as the service life of the entire bearing can be determined with great reliability [12-16].

An additional torque load occurs in the eccentrically loaded axial bearing. The influence of the torque on the load distribution between the rolling elements and on the service life of the axial ball bearing was analyzed in [18]. In this paper, contact stresses and deformations in an eccentrically loaded ball bearing with a contact angle of 90° and operating with rotational frequencies n ≤ 10 rpm will be analyzed in a slightly different way, by introducing two new quantities - load factor and eccentricity factor.

2. STRESS AND DEFORMATION IN THE BALL-RACEWAY CONTACT

In the unloaded ball bearing, there is point contact between the balls and the raceway groove. Transferring the load, balls and raceways are deformed in contact and the contact surface has an elliptical shape. The size of the contact ellipse depends on the elastic properties of the material, the dimensions of the contact surfaces and the load. Contact stresses and deformations in the ball-raceway contact can be determined using Hertz theory [1,2]. According to this theory, the dimensions of the contact ellipse can be determined, as well [17]. The equations for major and minor semiaxes of the contact ellipse at the place of every single i-th ball are:

$$a_{\mathrm{i}} = n_a \sqrt[3]{\frac{3}{2}\frac{(1-\nu^2)F_{\mathrm{i}}D_{\mathrm{w}}}{E(2-\xi)}}$$
$$b_{\mathrm{i}} = n_b \sqrt[3]{\frac{3}{2}\frac{(1-\nu^2)F_{\mathrm{i}}D_{\mathrm{w}}}{E(2-\xi)}} \tag{1}$$

where: F_{i} is normal load in the i-th ball-raceway contact; E is the modulus of elasticity of bearing's parts; ν is Poisson's ratio; n_a, n_b are functions of elliptic integrals [2]; $\xi = R_{\mathrm{w}}/R$; $D_{\mathrm{w}} = 2R_{\mathrm{w}}$ is the ball diameter; R_{w} and R are radii of the ball and raceway groove, respectively.

The quantities n_a and n_b in expression (1) are given in appropriate tables [2], as a function of the auxiliary quantity $\cos\tau$, which depends on the bearing type. For ball bearings, it can be determined from the expression [17]:

$$\cos\tau = \frac{\xi}{2-\xi} \tag{2}$$

The maximal ball-raceway contact stress is given by the expression [2]:

$$\sigma_{\max,\mathrm{i}} = \frac{3}{2}\frac{F_{\mathrm{i}}}{\pi a_{\mathrm{i}} b_{\mathrm{i}}} \tag{3}$$

The contact deformation in the ball-raceway contact is determined based on the expression [2]:

$$\delta_{\mathrm{i}} = C_F F_{\mathrm{i}}^{2/3} \tag{4}$$

The C_F constant in expression (4) depends on the bearing's internal geometry, modulus of elasticity, and Poisson's ratio. For thrust ball bearing, it can be determined based on the expression [17]:

$$C_F = \frac{3}{2}\left(\frac{2K}{\pi n_a}\right)\sqrt[3]{\frac{2}{3}\left(\frac{1-\nu}{E}\right)^2\frac{2-\xi}{D_{\mathrm{w}}}} \tag{5}$$

where $2K/\pi n_a$ is an auxiliary quantity given in appropriate tables [2] depending on $\cos\tau$.

The initial assumptions for the development of a mathematical model of load distribution in an axially loaded thrust ball bearing are:

- balls and washers are of ideal shape and dimensions;
- volume deformations of bearing parts are neglected;
- the angular distance between balls is equal;
- the bearing is statically loaded (n ≤ 10 rpm)
- bearing load (axial force) is of constant direction and intensity;
- one washer has an ideal (perpendicular) position to the bearing axis (no tilting) and has absolute volume and surface stiffness, ie. stress and deformation analysis will be done for the contact of the balls and the other washer, tilting due to the eccentric axial load.

The axially loaded thrust ball bearing is shown in Figure 1. The axial force is acting at a distance e from the bearing axis. The most unfavourable case is when the axial force intersects the radius vector of one of the balls (the 0-th ball in Fig. 1). Centric axial bearing loading is a special case of loading when $e = 0$.
Due to the eccentric loading, a tilting moment occurs as an additional load. The washer tilts by an angle θ (Fig. 1) causing additional contact deformations of the balls on the side of a force acting. The static equilibrium conditions of the bearing shown in Figure 1 can be written as follows:

$$F_{\mathrm{A}} = \sum_{\mathrm{i}=0}^{Z-1} F_{\mathrm{i}}$$
$$F_{\mathrm{A}} e = \frac{D_{\mathrm{p}}}{2}\sum_{\mathrm{i}=0}^{Z-1} F_{\mathrm{i}}\cos(\mathrm{i}\gamma) \tag{6}$$

where: Z is the number of balls in the bearing; e is eccentricity, ie. the distance between the F_{A} force line and the bearing axis; D_{p} is the bearing's pitch diameter [4,5].

The system of two equations (6) has Z unknown quantities. This is load F_{i} of every single ball of Z balls in the bearing. To determine all unknown quantities, it is necessary to introduce additional equations for contact deformations. Under the centric axial load F_{A}, deformations (δ_{a}) in the ball-raceway contact are equal for all balls. Due to the washer tilting under moment $F_{\mathrm{A}}e$ moment, with tilting angle θ (Fig. 1), there is an additional contact deformation of the balls located on the side of the external eccentric load acting (Fig. 1). The balls on the opposite side are relieved (Fig. 1) and their contact deformations are reduced, so they are not the subject of consideration in this paper. The contact deformations of individual balls differ, depending on their position to the point of external load F_{A}.

Based on the previous considerations, an expression can be written for the contact deformation at the location of every single i-th ball:

$$\delta_{\mathrm{i}} = \delta_{\mathrm{a}} + \delta_{\theta\mathrm{i}} \tag{7}$$

The contact deformation at the position of the i-th ball due to the washer tilting with tilting angle θ can be determined as follows:

$$\delta_{\theta\mathrm{i}} = \delta_{\theta} \cos(\mathrm{i}\gamma) \tag{8}$$

The contact deformation at the place of the most loaded "0" ball (i = 0), due to the washer tilting can be determined from expression (8) and based on Figure 1:

$$\delta_{\theta 0} = \delta_{\theta} = \theta \frac{D_{\mathrm{p}}}{2} \tag{9}$$

Based on expression (4), the load of the i-th ball can be determined:

$$F_{\mathrm{i}} = C_F^{-3/2} \delta_{\mathrm{i}}^{3/2} = C_{\delta} \delta_{\mathrm{i}}^{3/2} \tag{10}$$

By substituting expressions (7) and (10) in expression (6), we obtain:

$$\begin{aligned} \frac{F_{\mathrm{A}}}{C_{\delta}} &= \sum_{\mathrm{i}=0}^{Z\text{-}1} \left(\delta_{\mathrm{a}} + \delta_{\theta} \cos(\mathrm{i}\gamma)\right)^{3/2} \\ \frac{F_{\mathrm{A}}}{C_{\delta}} \cdot \frac{2e}{D_{\mathrm{p}}} &= \sum_{\mathrm{i}=0}^{Z\text{-}1} \left(\delta_{\mathrm{a}} + \delta_{\theta} \cos(\mathrm{i}\gamma)\right)^{3/2} \cos(\mathrm{i}\gamma) \end{aligned} \tag{11}$$

For considered thrust ball bearing, when the rotation speed is $n \leq 10$ rpm, a new value can be introduced - the load factor. It is a relative load, ie. external axial load F_{A} reduced to the static load rating C_0:

$$k_F = \frac{F_{\mathrm{A}}}{C_0} \tag{12}$$

For further analysis, the axial load eccentricity factor is introduced. It is a relative eccentricity, ie. eccentricity reduced to the bearing pitch radius:

$$k_e = \frac{e}{D_{\mathrm{p}}/2} \tag{13}$$

By introducing the load factor k_{F}, determined by expression (12) and the eccentricity factor k_{e}, defined by expression (13), equations (11) get the form:

$$\begin{aligned} k_F \frac{C_0}{C_{\delta}} &= \sum_{\mathrm{i}=0}^{Z\text{-}1} \left(\delta_{\mathrm{a}} + \delta_{\theta} \cos(\mathrm{i}\gamma)\right)^{3/2} \\ k_F k_e \frac{C_0}{C_{\delta}} &= \sum_{\mathrm{i}=0}^{Z\text{-}1} \left(\delta_{\mathrm{a}} + \delta_{\theta} \cos(\mathrm{i}\gamma)\right)^{3/2} \cos(\mathrm{i}\gamma) \end{aligned} \tag{14}$$

Expressions (14) are a system of two equations with two unknown quantities (contact deformations δ_{a} and δ_{θ}). It is a system of nonlinear equations that are solved iteratively, using some of the numerical methods. In this case, the MathCAD program was used for that purpose.

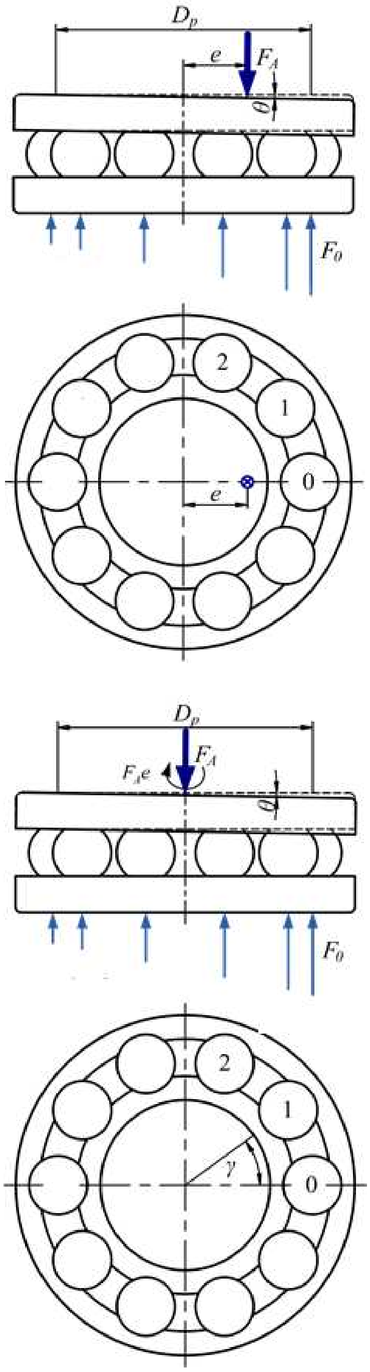

Fig.1. Eccentrically loaded thrust ball bearing

3. NUMERICAL EXAMPLE AND DISCUSSION OF RESULTS

The following analysis is carried out for thrust ball bearings with bore diameter d = 30 mm, of all standard series: 511, 512, 513 and 514 (Table 1).
Large and small semi-axes of contact ellipses, contact stress and deformations are determined using expressions (1)-(5). Four cases of bearing load were analyzed: 25%,

50%, 75% and 100% of the static load rating, ie. load factor values k_F = {0.25; 0.50; 0.75; 1.00}. Considered eccentricities are corresponding to the values of the eccentricity factor k_e = {0; 0.1; 0.2; 0.3; 0.4; 0.5}, including zero eccentricity loading (centric loading).

Table 1. The main parameters of thrust ball bearings with a bore diameter of 30 mm

Quantity		511	512	513	514
Bore diameter, mm	d	30			
Outer diameter, mm	D	47	52	60	70
Pitch diameter, mm	D_p	38.5	41	45	50
Number of balls	Z	18	12	10	8
Angle between balls, °	γ	20	30	36	45
Ball diameter, mm	D_w	6.00	7.98	10.32	15.08
Raceway radius, mm	R	3.23	4.29	5.54	8.12
$R_w/R = D_w/2R_w$	ξ	0.93			
Poisson's ratio	ν	0.3			
Modulus of elasticity, N/mm^2	E	$2.1 \cdot 10^5$			
Static load rating, kN	C_0	43	51	65	122
Auxiliary quantity	$\cos\tau$	0.82			
Constant, 10^{-4} mm/N$^{2/3}$	C_F	1.28	1.17	1.07	0.95
Constant, 10^5 N/mm$^{3/2}$	C_δ	6.9	7.9	9.0	10.8

Contact deformations caused by both external axial load and the washer tilting moment due to eccentricity were calculated by solving the equation system (14). The sum of these deformations is the contact deformation of the most loaded ball (the load distribution is unequal due to eccentricity). Then, using expression (10), the normal load of the most loaded ball was determined.

Based on expression (1), the dimensions of the contact ellipse at the position of the most loaded ball are determined. And, finally, the maximum contact stress of the most loaded ball is determined from expression (3). Results are shown by diagrams in Figures 2-8.

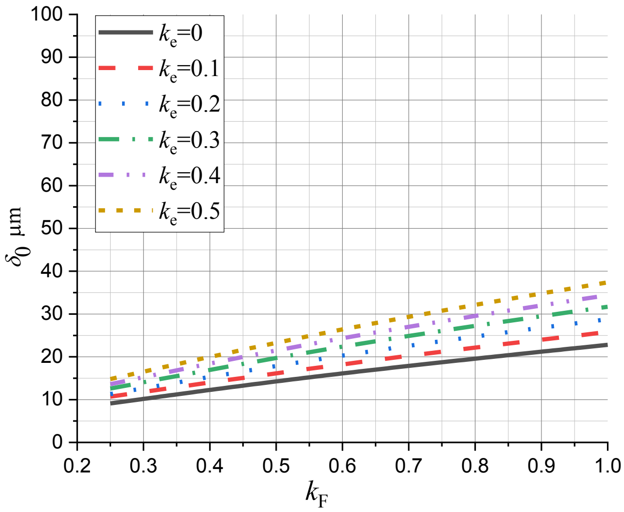

Fig. 2. Contact deformation of the most loaded ball of the eccentrically loaded bearing 51106, depending on the load and eccentricity

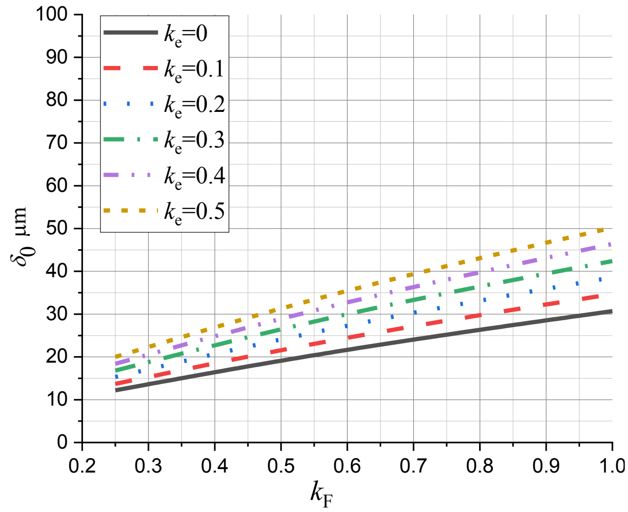

Fig. 3. Contact deformation of the most loaded ball of the eccentrically loaded bearing 51206, depending on the load and eccentricity

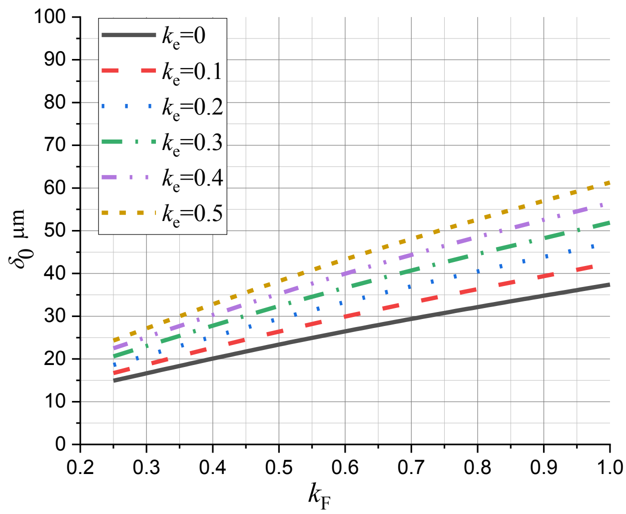

Fig. 4. Contact deformation of the most loaded ball of the eccentrically loaded bearing 51306, depending on the load and eccentricity

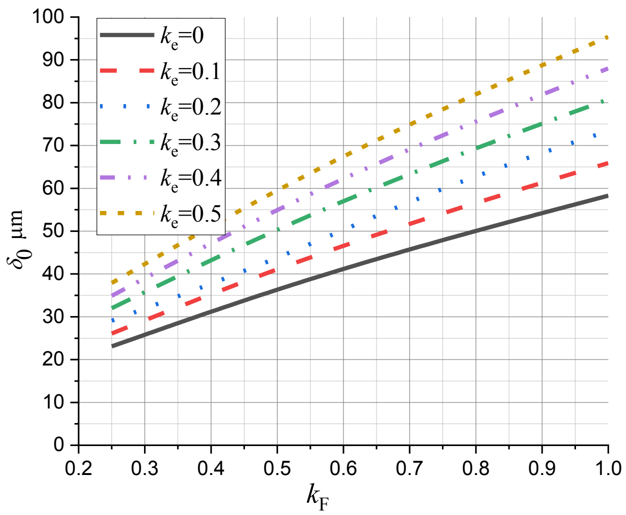

Fig. 5. Contact deformation of the most loaded ball of the eccentrically loaded bearing 51406, depending on the load and eccentricity

Based on diagrams for contact deformation δ_0 of the most loaded ("0") ball in contact with the raceway of eccentrically loaded thrust ball bearings (series 51106, 51206, 51306 and 51406), shown in Figures 2-5, it can be concluded that the contact deformation of the "0"-ball increases 2.5 times with increasing load (k_F = 0.25…1) and 1.64 times with increasing eccentricity (k_e = 0…0,5).
Diagrams in Figure 6 shows how all deformations, due to axial load, tilting moment and total one, change due to eccentricity. Axial deformations slightly decreases, but tilting deformation increasing is significantly. The reason of that is unequal load distribution in loaded zone. In this case all balls in this zone additionally take part of external load, grater than in the case of equal load distribution, ie. centric loading.

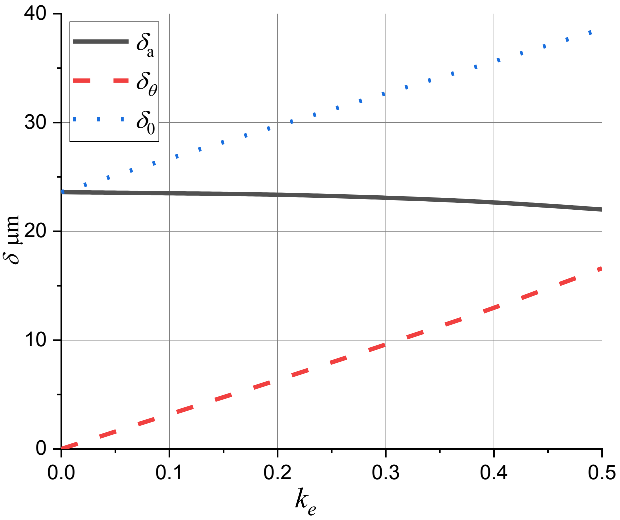

Fig. 6. Contact deformations caused by axial load and tilting moment, depending on eccentricity (for thrust ball bearing 51206 loaded with F_A =0.5C_0)

Based on diagrams of the maximum stress $\sigma_{max,0}$ in the ball-raceway contact in eccentrically loaded thrust ball bearings of series 51106 (the lighter one) and 51406 (the havier one), shown in Figures 7 and 8, it can be concluded that contact stress increases with increasing load and eccentricity. In the thrust ball bearing under the centric external axial load, limited contact stress of 4200 N/mm^2 is determined by the static load capacity C_0 [4].The values obtained in this paper, for the condition when the external axial load is equal to the static load capacity (F_A = C_0, ie. k_F = 1), are approximately 4500 N/mm2. This is an acceptable deviation since this difference is influenced by the constant C_δ, given in Equation (10) and Table 1, depending on bearing parts' material properties and geometry. These are also the parameters influenced by bearing manufacturer. Digarams from Figures 7 and 8 show that for considered bearings, contact stress does not exceed 4200 N/mm^2 for k_e ≈ (0.3 ... 0.4) and small eccentricities of k_e < 0.3.
By comparing bearings of different series, from light to heavy one, the load of the balls is increased, but the maximum contact stress between the balls and the raceway is approximately the same for all series (Fig. 7 and 8). This is due to the increase of contact surfaces between the balls and the groove of raceway – contact ellipses. [17].

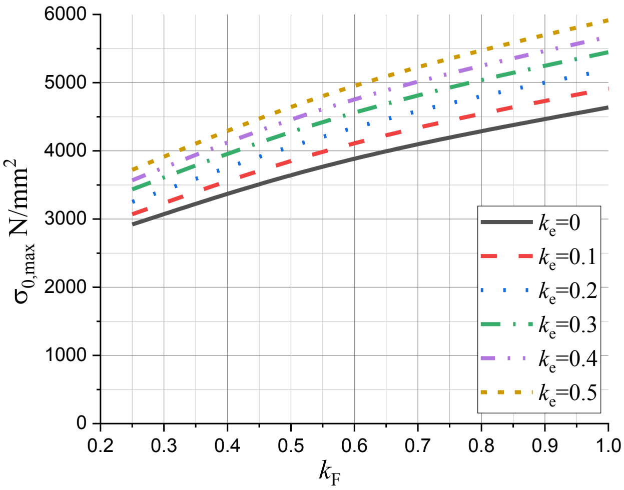

Fig. 7. Contact stress of the most loaded ball of the eccentrically loaded bearing 51106, depending on the load and eccentricity

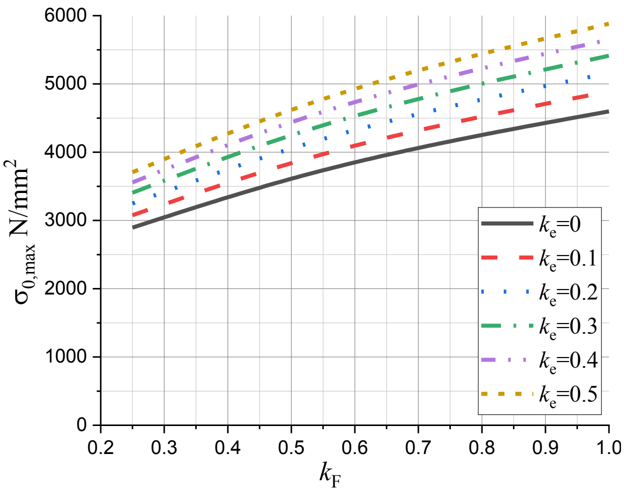

Fig. 8. Contact stress of the most loaded ball of the eccentrically loaded bearing 51306, depending on the load and eccentricity

4. CONCLUSION

In this paper, deformations and stresses in the contact of balls with the raceways of thrust ball bearings with a contact angle of 90° and operating with rotational frequencies n ≤ 10 rpm (statically loaded axial bearings) are considered. Ideally, the direction of the axial load should coincide with the bearing axis. In reality, there are minor or major deviations. It leads to unequal load distribution when one ball is loaded more than all others. Therefore, both the contact deformation and the stress at the location of this ball are the greatest. Their values limit the bearing capacity of a real bearing, which is less than the bearing capacity of an ideal centrically loaded bearing. Conventional roller bearing theory and corresponding ISO do not consider eccentrically loaded ball bearings. Analyzes have shown that the considered bearings 51106, 51206, 51306 and 51406 can perform their function smoothly at low speeds (n ≤ 10 rpm), even if there is semo eccentricity of the external load and if the external axial load is not more than 30- 40% of static load rate. Otherwise, additional bearing capacity analyzes are required. The carried out analyzes and the obtained results can be the basis for further research of the loading rate of thrust ball bearing under eccentric external axial load, ie unequal load distribution between the balls. In this case, the contact stress at the place of the most loaded ball can be higher than the limit value and can cause unforeseen premature and excessive raceway surface damage. The results can be used for a more accurate assessment of the thrust ball bearing capacity, as well as in case studies for failure analysis.

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REFERENCES

[1] Krsmanović, V., Mitrović, R.: *Sliding and rolling bearings* (in Serbian), University of Belgrade, Faculty of Mechanical Engineering, Belgrade, ISBN 978-86-17-19284-4, 2015

[2] Harris, T.A.: Rolling Bearing Analysis, John Wiley and Sons, New York, ISBN 0-471-35457-0, 2001

[3] Rumbarger, J.: Thrust bearing with eccentric loads, *Machine Design*, 1962

[4] ISO 76:2006 Rolling bearings – Static load ratings

[5] ISO 281:1990 Rolling bearings – Dynamic load ratings and rating life

[6] Gold, P.W., Loos, J.: Wear resistance of PVD-coatings in roller bearings, *Wear*, 253, pp. 465-472, ISSN 0043-1648, 2002

[7] Aguirrebeitia, J., Avilés, R., Fernandéz de Bustos, I., Abasolo, M.: Calculation of general static load-carrying capacity for the design of four-contact-point slewing bearings, *Transactions of ASME Journal of Mechanical Engineering*, 132, pp. 064501/1-6, ISSN 0738-0666, 2010

[8] Cousseau, T., Graça, B., Campos, A. and Seabra J.: Friction torque in grease lubricated thrust ball bearings, *Tribology International*, 44, pp. 523-531, ISSN 0301-679X, 2011

[9] Ren, Z., Wang, J., Guo, F. and Lubrecht, A.A.: Experimental and numerical study of the effect of raceway waviness on the oil film in thrust ball bearings, *Tribology International*, 73, pp. 1-9, ISSN 0301-679X, 2014

[10] Cousseau, T., Graça, B.M., Campos, A.V. and Seabra J.H.O.: Influence of grease rheology on thrust ball bearings friction torque, *Tribology International*, 46, pp. 106-113, ISSN 0301-679X, 2012

[11] Fernandez, C.M.C., Marques, P.M.T., Martins, R. and Seabra J.H.O.: Gearbox power loss. Part I: Losses in rolling bearings, *Tribology International*, 88, pp. 298-308, ISSN 0301-679X, 2015

[12] Ristivojević, M., Mitrović, R.: *Load distribution – Gears and rolling bearings* (in Serbian), University of Belgrade, Faculty of Mechanical Engineering, Belgrade, ISBN 86-7558-112-2, 2002

[13] Lazović, T., Mitrović, R., Ristivojević, M.*: Load distribution between rolling elements of ball and roller bearing*, Proceedings of 3rd International Conference Research and Development in Mechanical Industry – RaDMI'03, 19-23 September, Herceg Novi, Montenegro, pp. 11-19, 2003

[14] Lazović, T., Ristivojević, M., Mitrović, R.: Mathematical model of load distribution in rolling bearing, *FME Transactions*, 36, pp. 189-196, ISSN 1451-2092, 2008.

[15] Lazović, T., Mitrović, R., Ristivojević, M.: Influence of internal radial clearance on the ball bearing service life, *Journal of the Balkan tribological association*, 16 (1), pp. 1-8, ISSN 1310-4772, 2010

[16] Lazović, T.: *Service life of ball bearings* (in Serbian), University of Belgrade, Faculty of mechanical engineering, Belgrade, ISBN 978-86-6060-082-2, 2021

[17] Lazović, T., Varagić, S., Milović, LJ.: Contact stress and deformations in thrust ball bearing, *Journal of Machine Design*, 10, 3, pp. 85-92, ISSN, 2018

[18] Tianyu, L. and Jiwei, L.: *The influence of moment load on fatigue life of thrust ball bearing*, Proceedings of the International Conference on Mechanical Engineering and Material Science - MEMS, 28-30 December, Shanghai, China pp. 25-28, 2012

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SEALING OF THE HIGH SPEED BEARING ASSEMBLIES WITH ONE ELASTIC SUPPORT

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Abstract: *High speed bearing assemblies are widely applied in many industries, especially in the airspace and automotive. Design of these assemblies is highly challenging due to some opposed factors affecting their proper functionality. On the one side, there is a condition of rotor-dynamics, which implies the shaft to rotate as stable as possible, retaining its original shape. In regards to this, it was observed that having one elastic and one stiff support, rather than having two stiff supports, provides better dynamic behaviour. On the other side, due to high rotational speed, these assemblies have to be sealed contactlessly, by means of labyrinth, centrifugal or similar types of seals. These seals operate with very small gaps between their rotor and stator. In order to obtain the lowest possible gap in the sealing which allows displacements of the shaft supported by one elastic and one stiff support, a specific design solution is developed. Testing procedure and results, together with design solutions are presented in this paper.*

Keywords: *centrifugal seal, high speed assembly sealing, bearing stiff and elastic support*

1. INTRODUCTION

With the development of high speed assemblies the special attention was applied to sealing solutions. Due to high speeds, use of the contact seals would result in a great amount of losses, in the form of released heat. Thus, the contactless seals came up as a convenient solution, becoming a subject of many researches.

An interesting overview of the seals in high speed assemblies (aircraft gearboxes) was brought by Rahman et al. [1], while the overview of the labyrinth seals is presented by de Souza Barros et al. [2]. Guoqing Li et al. [3] examined a centrifugal seal with the oil-throwing tooth, different from the gas sealing – labyrinth seals. Subramanian et al. [4] performed a numerical calculation on the labyrinth seal, taking into account its centrifugal growth. The same authors extended their research by examining influence of both, centrifugal and thermal effect calculated by CFD software [5]. Nowadays, the centrifugal seals are improved by introducing sealing fluid, brought into the seals through special inlets [6].

In order to satisfy a rotor-dynamics criteria of the compressor shaft, many design solutions were proposed. Some examples are analysed and presented by Kolarević et al. [7]. It is observed that having one stiff and one radially elastic or both elastic supports on the shaft, provides much better rotor-dynamic behaviour (lower radial displacements along the shaft), if compared to both stiff supports. The influence of the bearing support flexibility onto the prediction of the critical speeds of the rotor was analysed back in 2008 by Nicholas et al. [8]. They proposed analytical model as well as experimental verification for 4 types of rotor. Design solution in which the one support is put into the squirrel cage, provides radial elasticity on that support. The squirrel cage elasticity is calculated and optimized for the given criteria. Zhang et al. proposed a multi-objective optimization method and confirmed it experimentally [9]. Wang et al. proposed a new mapping approach to optimize the shape of the squirrel cage slots [10].

2. DESIGN TASKS AND SOLUTION

The unit under test (UUT) is the bearing assembly for turbo shaft engine TSE-200 Phoenix of the company EDePro, which operates at 60000 RPM. In order to obtain the operation at this regime, it is necessary to design contactless seal. Any contact on such high speeds, would result in enormous friction losses and wear. Some of the possible solutions for the high speed assembly sealing would be labyrinth seal (Fig. *1*, a), which consists of a very long and relatively narrow (snake like) gap, causing significant pressure drop which prevents oil leakage. Another solution is centrifugal seal (Fig. *1*, b) [11]. The rotor of this seal is designed to have "steps and teeth" and, when rotates, it forces oil radially to the chambers on the seal stator. The oil is collected in these chambers, then forced by gravity and drainage pump into the drain out system. The second solution, a two stage (two chambers) centrifugal seal is adopted for further development.

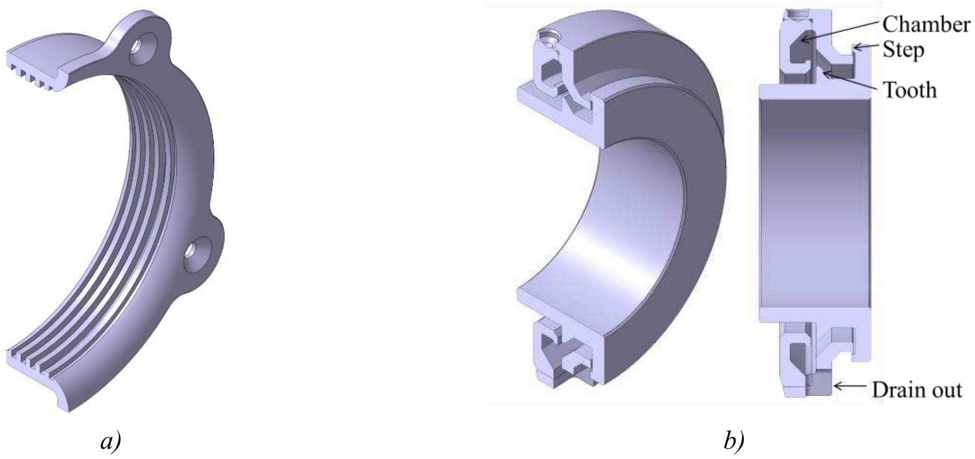

Fig. 1. a) Labyrinth seal, b) Centrifugal seal

Another specific condition of this bearing assembly is imposed by rotor-dynamic. As noted before in this paper, the behaviour of the high-speed shafts is much more favourable if they are supported by one elastic and one stiff support (Fig. *2*). Although it improves the rotor-dynamic behaviour of the rotor, the presence of the elastic support causes the gaps in the centrifugal seal to vary, with respect do radial displacements allowed by that elastic support.

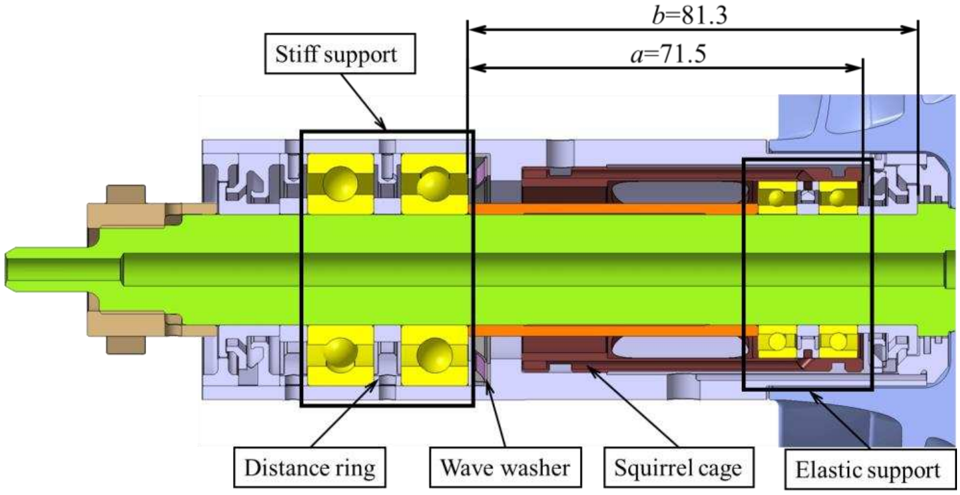

Fig. 2. Bearing assembly of jet engine with one stiff and one elastic support

The more radial freedom in the elastic support, the higher variations of the seal gap between rotor and stator. I.e. when the squirrel cage is not deformed, which is in the stationary mode, the gap in the seal has a uniform circumferential value. On the other hand, extreme gaps occur when the shaft is on the full speed rotation, and the squirrel cage deformations are maximal. By extreme gaps, it is assumed a minimal gap in one point of the shaft circumference, while at the same time the gap is maximal at the opposite point of the shaft circumference.

To secure the proper run of the assembly, a contact between the rotor and the stator should be avoided. Thus, the gap between the rotor and stator of the seal has to be greater than the gap between elastic cage and the bearing housing (Figure 3), which in this specific case equals 0.2 mm.

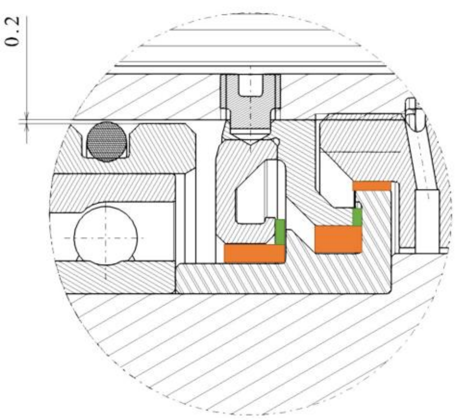

Figure 3. Axial and radial gaps in the seal, with respect to radial gap between elastic cage and bearing housing

Taking into account that the elastic cage possible displacement (a radial gap between the cage and the bearing housing) is designed to be g=0.2 mm, and regarding the proportion of the dimensions in *Fig. 2*, a minimal radial gap between the seal rotor and stator could be calculated:

$$g_x = \frac{b}{a} \cdot g = \frac{81.3}{71.5} \cdot 0.2 = 0.227 \text{ mm} \quad (1)$$

According to this equation, and for the sake of safety in preventing the contact between the seal rotor and stator, the minimal gap is slightly increased and set to 0.3 mm.

To obtain the constant preload of the bearings, on the right side of the stiff support there is placed a special type of spring called wave washer, which is compressed for about 0.5 mm in the mounting position (*Fig. 2*). Between the bearings there are distant rings, through which is the oil brought to the bearings. Separation of bearings with distant rings, allows run on higher RPM for bearings, then it would be the case without the distant rings.

3. EXPERIMENTAL VERIFICATION

In order to verify the efficiency of the centrifugal seal, two tests were conducted – stationary and dynamic.

In the first test, the shaft was not rotating (stationary tests), and the sealing is provided only by under-pressure in seal chambers created by means of the draining pump, which forces the lubricant into the draining pipes. During the second test, the shaft rotates at the maximum speed (dynamic tests) and, in addition to draining pump, the centrifugal force also helps for directing lubricant into the drainage pipes. Both tests are supposed to give the answer on how much oil could be brought into the bearing assembly, before it comes to the leakage through the seals. Measured parameters during the tests were flow rates of oil on both, stiff and elastic support separately. Also the temperatures of the bearings were measured, in order to verify the proper run of the assembly.

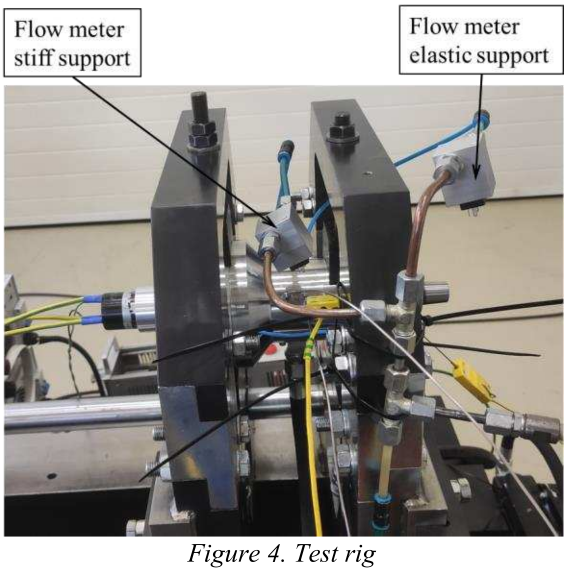

Figure 4. Test rig

From the results presented in the Table 1 it can be concluded that centrifugal seal in a dynamic regime allows about 27% higher oil flow than in a stationary regime.

Table 1. Flow rates of oil on which occurred the leakage on the seal, for the stationary and the dynamic test

	Flow rate on stiff support [g/s]	Flow rate on elastic support [g/s]	Total flow [g/s]
Stationary test	11	4,5	15.5
Dynamic test	13	6,7	19.7

These numbers are taken to define the regime of the engines' start-up. While accelerating from zero to 30000 RPM, the oil flow rates on stiff and elastic support are slightly lower than maximums in the stationary regime tests, and are respectively 10 g/s and 4 g/s. Then the flows are increased to 12 g/s and 5 g/s, and kept on these values while on full working regime.

It is important to note that bearing temperatures did not exceed 85 °C, while maximum allowed temperature for this type of bearings is 200 °C. This indicates that amount of oil brought to the bearings is enough to provide proper lubrication.

4. CONCLUSION

The task of the research was to develop and test a contactless seal for high speed assembly which can operate efficiently, placed next to the elastic support (bearing that has certain degree of freedom in radial direction). For a suitable solution it is chosen a centrifugal, two stage contactless seal.

In order to avoid clash inside the seal, its radial gap is calculated with respect to the maximal radial displacement of the elastic support (the difference between the inner radius of the bearings' housing and outer radius of the squirrel cage).

The sealing abilities of the centrifugal seals are tested experimentally. When the shaft rotates on maximum, the leakage on the seal occurs if the total oil flow exceeds 19.7 g/s. When the shaft is not rotating, the leakage occurs when total oil flow exceeds 15.5 g/s. If comparing these values, it could be observed seal performance improvement of 27% in dynamic regime. Also, it should be noted that the values obtained by tests are satisfactory for the amount of oil necessary for the lubrication of the UUT.

Further development of these seals could go in direction of introducing compressed fluid into the seal chambers, in order to improve the sealing performances. This compressed fluid could be air brought from the compressor of jet engine, or some external compressing device through the separate installation.

ACKNOWLEDGMENT

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REFERENCES

[1] Rahman A. H., Basha J.: Dynamic Seals For High Speed Aircraft Gearbox, Journal on Design and Manufacturing Technologies, Vol.1, No.1, pp. 24-29, 2007

[2] de Souza Barros G. P., Martinez C. B., de Faria Viana, E. M, Diniz H. A. G., Duarte W. M.: Labyrinth Seals - a Literature Review, 17th Brazilian Congress of Thermal Sciences and Engineering, Águas de Lindóia, SP, Brazil, 2018

[3] Li G., Zhang Q., Lei Z., Huang E., Wu H., Xu G.: Leakage performance of labyrinth seal for oil sealing of aero-engine, Propulsion and Power Research, Vol. 8, No. 1, pp. 13-22, 2019

[4] Subramanian S., Sekhar A.S., Prasad B.V.S.S.S.: Rotordynamic characteristics of rotating labyrinth gas turbine seal, with centrifugal growth, Tribology International, Vol. 97, pp. 349-359, 2016

[5] Subramanian S., Sekhar A.S., Prasad B.V.S.S.S.: Rotordynamic characterization of rotating labyrinth gas turbine seals with radial growth: Combined centrifugal and thermal effects, International Journal of Mechanical Sciences, Vol. 123, pp. 1-19, 2017

[6] Kunyi C., Shuangxi L.: Experimental Study on the Performance of the Gas Centrifugal Seal with Continuous Injection and Discharge of Sealing Fluid, IOP Conference Series: Materials Science and Engineering, Vol. 1081, 2021

[7] Kolarević N., Micković D., Crnojević S., Stanković M., Ognjanović M., Miloš M.: Dynamic stability of high speed turboshaft engine with reducer, IOP Conf. Series: Materials Science and Engineering Vol. 393, The 10th International Symposium Machine and Industrial Design in Mechanical Engineering (KOD 2018), 6-8 June 2018, Novi Sad, Serbia

[8] Nicholas J. C., Barrett L. E.: The Effect of Bearing Support Flexibility on Critical Speed Prediction, ASLE Transactions, Vol. 29, No. 3, pp. 329-338, 1986, DOI: 10.1080/05698198608981693

[9] Zhang W., Han B., Li X., Sun J., Ding Q.: Multiple-objective design optimization of squirrel cage for squeeze film damper by using cell mapping method and experimental validation, Mechanism and Machine Theory, Vol. 132, pp. 66-79, 2019

[10] Wang D., Zhang W., Wang Z.P., Zhu J.H.: Shape optimization of 3D curved slots and its application to the squirrel-cage elastic support design, Science China Physics, Mechanics And Astronomy, Vol. 53, No. 10, pp. 1895–1900, 2010

[11] SKF, PUB BU/P1 13383/2 EN • March 2016, page 96

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ASPECTS REGARDING MATERIALS USED IN NON-METALLIC ELEMENTS CONSTRUCTION OF ELASTIC COUPLINGS

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Viorel ȘIȘMAN
Ion – Marius GHIȚESCU

Abstract: *This paper presents aspects regarding the construction of couplings with bolts using non-metallic elements, having different hardness, the elements involved in torque transmission, in this case elastic elements, having also different dimensions or forms, in the way to have a good elasticity and capacity of vibration absorbtion. In paper there are also presented: the construction of non-metallic elements, influence of material characteristics and limit and loading conditions on the states of displacements, Von Misses stress and principal tensions. The modeling of the nonmetallic element is made for different qualities of rubber, using FEM method.*

Keywords: *elastic coupling; cylindrical bolts; nonmetallic element; finite element method;*

1. INTRODUCTION

Couplings with non-metallic elements are included in the category of elastic couplings [1 … 7]. They make the connection between two consistent elements of a kinematics chain. The purpose of such a connection is to transmit power (torque and rotational motion) without altering the kinematics functions.

The elastic couplings with non-metallic elements presented in [1 …7], accomplish the following functions: transmissions of rotation motion and moment torsion; damping of shocks and vibration; taking over axial, radial, angular/mixed deviations. The construction of coupling and elastic elements was also presented.

Near the elastic longitudinal module, practical determined, it is necessary to establish the stress values, researches made on different qualities of rubber, or different forms of intermediary element.

2. THE STRESS AND DEFORMATION ANALISE OF NON-METALLIC ELEMENT

The FEM analyze of elements having different qualities of rubber is based on some hypothesis of nonlinear viscous-elastic behavior of material used for non-metallic form. The modeling of non-metallic element was realized with CATIA *V5R21 software* [8, 9, 10].

The studied form of elastic element is presented in figure 1 [11, 12]. The finite element method allows the choice of an appropriate theoretical model, as a three-dimensional medium with visco-elastic properties. In this way, information can be obtained about the behavior of the material with a high degree of accuracy.

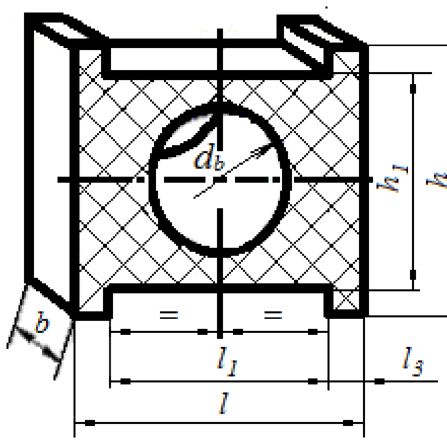


Fig.1. Shape of nonmetallic elements

In the finite element analysis, in the first stage the design of the piece to be analyzed is studied, establishing the geometric dimensions; the place and size of the request, the mode of constrain and the degrees of freedom dissolved.

To perform finite element modeling, determine the type of finite element that will be used.

For the non-metallic element model shown in Figure 1, the material characteristics corresponding to ethylene propylene rubber (EPDM), respective of natural rubber (NR) .

3. PROBLEM SOLUTION

In order to establish the loads applied on the studied model, a functional analysis of the group on components plates - rubber gasket - bolt / bolts was performed and taking into account the restrictions presented in figure 2 and 3.
The non-metallic element was supported on the left side on the side surface, inwards, of the foot of this shape and embedded on its side surface located on the outside on the right side of this shape.

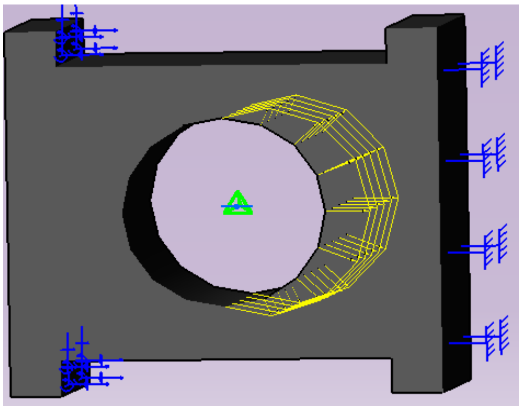


Fig.2. The restrictions and parabolic distribution of applied force

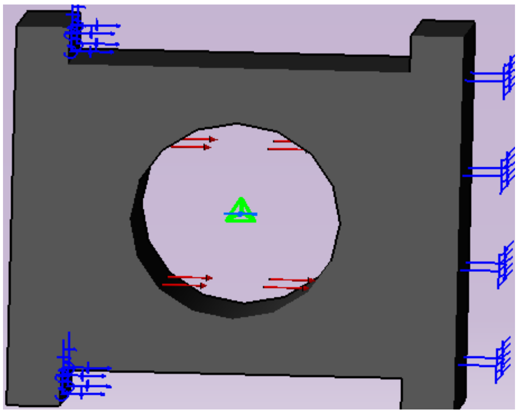


Fig.3. The restrictions and uniform radial distribution of applied force

In figure 2 was applied a parabolic distribution of force, and in figure 3 was applied a uniform distribution of force.
So, for this form of non-metallic element was applied, in those two cases corresponding material characteristics of ethylene propylene rubber (EPDM, a force by value F=166 N, on the interior circularly surface, by d_b=16 mm diameter; this force corresponds to the capable theoretical torsion moment, M_t = 41360 Nmm.
The states of displacements and tensions, in case of material characteristic corresponded of ethylene propylene rubber (EPDM) shape and parabolic distribution of force, are presenting in figures 4…6.
In figure 4, the maximum deflection of non-metallic element is 1,02 mm and it appears in the circular zone where it was applied the radial force, distributed parabolic.
In non-metallic element appears Von Mises tensions (equivalent tensions, see figure 5), and different values between $2{,}14*10^4 \ldots 1{,}12*10^6$ N/m^2.
The principal tensions (compression/traction) from ethylene propylene rubber (EPDM) shape as can be seen in figure 6, have a variation between ($-$ $2{,}01*10^6$ ... $1{,}68*10^6$) N/m^2.

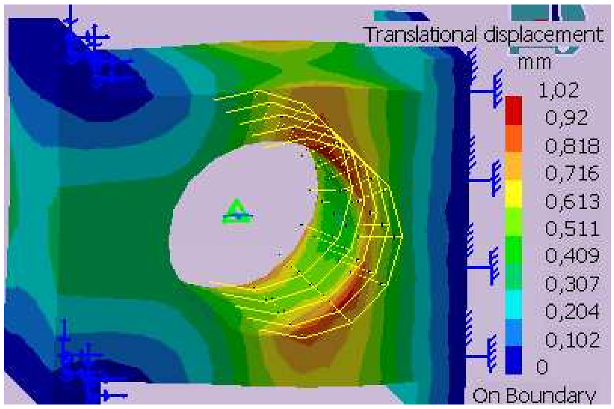


Fig.4. The displacement of EPDM shape for parabolic distribution of applied force

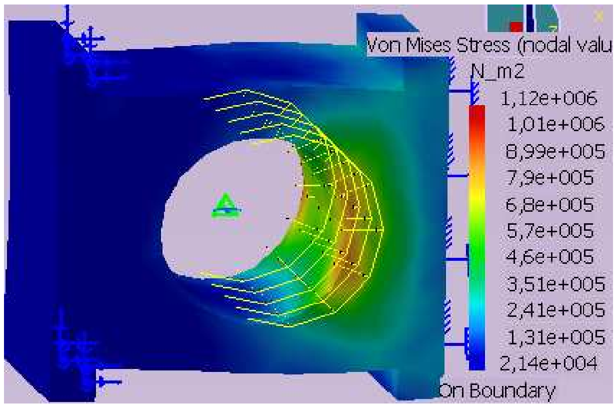


Fig.5. Von Mises Stress in EPDM shape for parabolic distribution of applied force

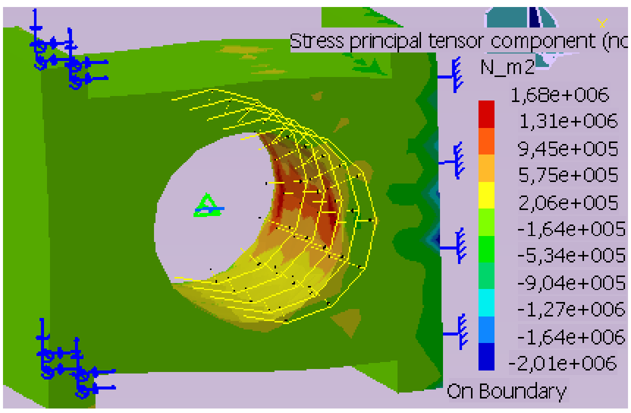


Fig.6. The principal tensions in EPDM shape for parabolic distribution of applied force

The states of displacements and tensions, in case of material characteristic corresponded of ethylene propylene rubber (EPDM) shape and it's applied a radial distribution of force, are presenting in figures 7…9. In figure 7, the maximum deflection of non-metallic element is 1,32 mm and it appears in the circular zone where it was applied the radial force, distributed uniform.

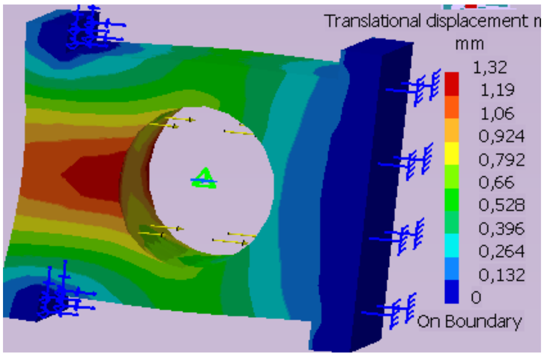


Fig.7. The displacement of EPDM shape for radial distribution of applied force

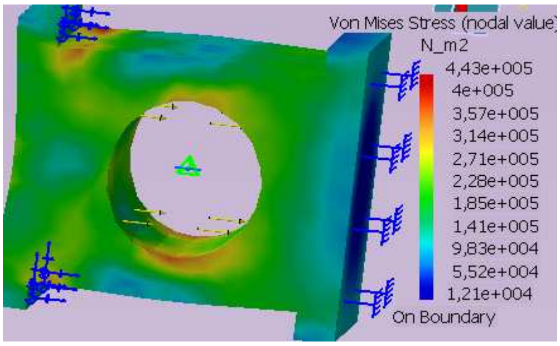


Fig.8. Von Mises Stress in EPDM shape for radial distribution of applied force

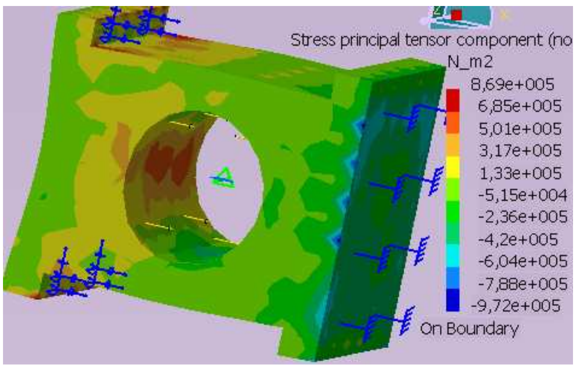


Fig.9. The principal tensions in EPDM shape for radial distribution of applied force

For radial distribution of applied force, in non-metallic element realized from EPDM rubber appears Von Mises tensions (equivalent tensions, see figure 8), and different values between $1{,}21*10^4$... $4{,}43*10^6$ N/m^2. The principal tensions (compression/traction) as can be seen in figure 9, have a variation between ($-$ $9{,}72*10^5$ ... $8{,}69*10^5$) N/m^2. Next, the shape in Figure 2 was analyzed by the finite element method applying mechanical material characteristics corresponding to natural rubber NR and applying a force F = 166 N uniformly distributed in the radial direction (see fig. 10…12).

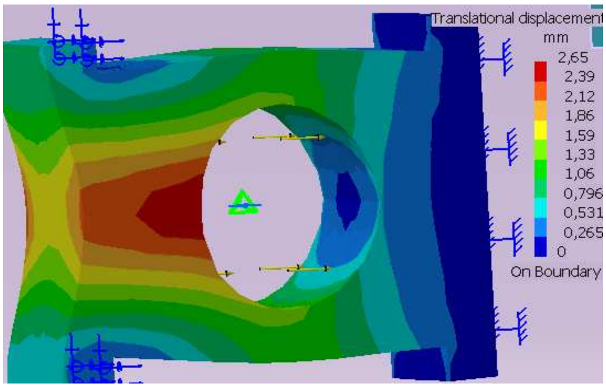


Fig.10. The displacement of NR shape for radial distribution of applied force

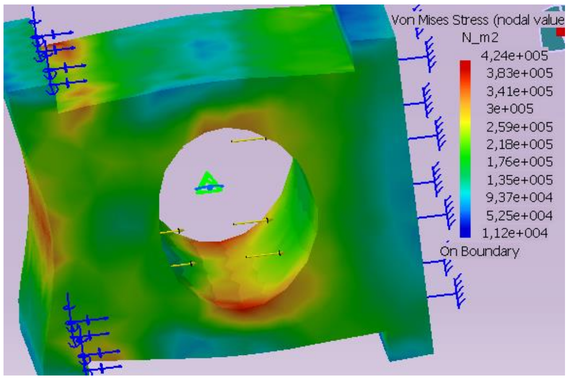


Fig.11. Von Mises Stress in NR shape for radial distribution of applied force

In figure 10, the maximum deflection of non-metallic element is 2,65 mm and it appears in the circular zone where it was applied the radial force, distributed uniform. For radial distribution of applied force, in non-metallic element realized from NR rubber appears Von Mises tensions (equivalent tensions, see figure 11), and different values between ($1{,}12*10^4$... $4{,}24*10^6$) N/m^2. The principal tensions (compression/traction) as can be seen in figure 9, have a variation between ($-$ $1{,}03*10^6$ ... $6{,}45*10^5$) N/m^2.

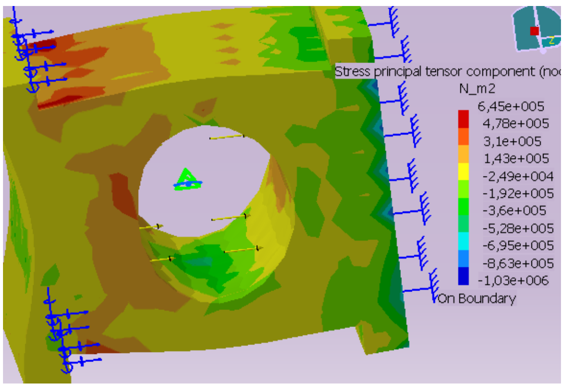


Fig.12. The principal tensions in NR shape for radial distribution of applied force

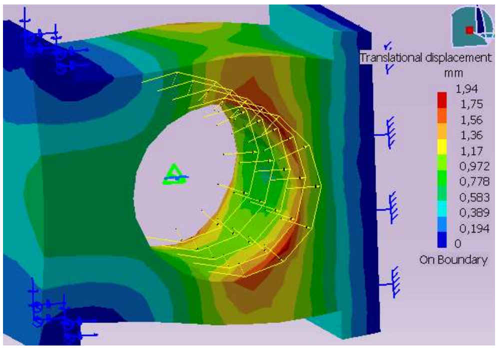


Fig.13. The displacement of NR shape for parabolic distribution of applied force

In figure 13, the maximum deflection of non-metallic element is 1,94 mm and it appears in the circular zone where it was applied the force distributed parabolic. In non-metallic element appears Von Mises tensions (equivalent tensions, see figure 14), and different values between ($1{,}96{*}10^4 \ldots 1{,}12{*}10^6$) N/m^2, for parabolic distribution of applied force. The principal tensions (compression/traction) as can be seen in figure 15, have a variation between ($-\,2{,}02{*}10^6 \ldots 1{,}69{*}10^6$) N/m^2.

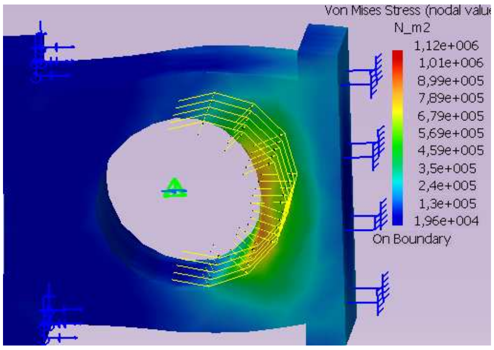


Fig14. Von Mises Stress in NR shape for parabolic distribution of applied force

The shape in figure 2 was analyzed by the finite element method applying mechanical characteristics of material corresponding to natural rubber NR and applying a force F = 166 N distributed parabolic (see fig. 13 -15).

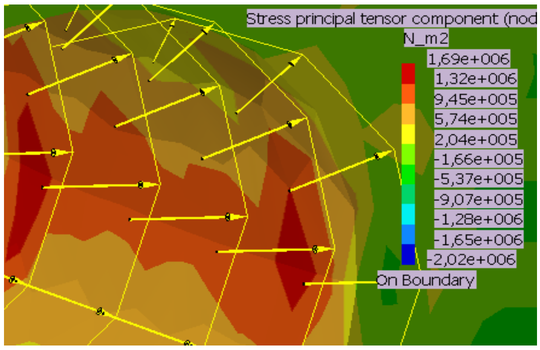


Fig.15. The principal tensions in NR shape for parabolic distribution of applied force

Table 1 shows the finite element modeling results of the non-metallic element in fig. 2 which has been assigned mechanical characteristics corresponding to the Ethylene propylene EPDM rubber, under the conditions of applying a force F = 166N (distributed parabolically, respectively radially uniform) and under various limit conditions. Table 2 shows the results of finite element modeling of the non-metallic element, shown in fig. 2, with mechanical characteristics corresponding to natural rubber NR, under the conditions of applying a force F = 166N, in various limit and loading conditions.
From the synthesis of the data obtained for the previously analyzed shape, the diagrams presented in figures 16 ... 18 were drawn, which allow a comparative analysis of the possibilities of deformation of the non-metallic element (fig. 16), of the Von Mises stresses (fig. 17) and main (fig. 18) that appear in the non-metallic element, for different qualities of rubber (NR, EPDM).

Table 1. The results of modeling – Ethylene propylene rubber EPDM shape and F=166N

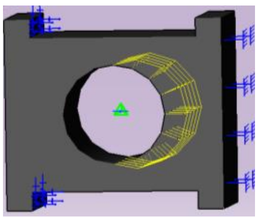
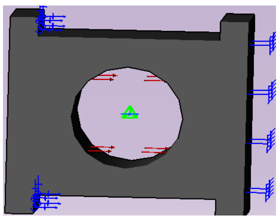
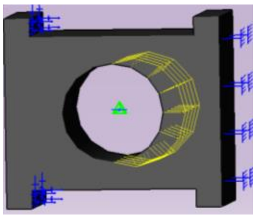
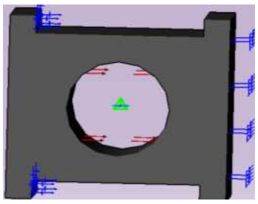
No	Applied material	Limit and loading conditions	Obtained results behind modeling
1.	Ethylene propylene rubber (EPDM)	Parabolic distribution of force 	• Maxim Displacement: 1,02 mm • Von Mises Stress: ($2{,}14{*}10^4 \ldots 1{,}12{*}10^6$) N/m^2 • Principal Tensions: ($-\,2{,}01{*}10^6 \ldots 1{,}68{*}10^6$) N/m^2
		Uniform radial distribution of force 	• Maxim Displacement: 1,32 mm • Von Mises Stress: ($1{,}21{*}10^4 \ldots 4{,}43{*}10^6$) N/m^2 • Principal Tensions:($-\,9{,}72{*}10^5 \ldots 8{,}69{*}10^5$) N/m^2

Table 2. The results of modeling – Natural Rubber NR shape and F=166N

No	Applied material	Limit and loading conditions	Obtained results behind modeling
1.	Natural Rubber	Parabolic distribution 	• Maxim Displacement: 1,94 mm • Von Mises Stress: ($1{,}96*10^4$...$1{,}12*10^6$) N/m^2 • Principal Tensions: (– $2{,}02*10^6$ ... $1{,}69*10^6$)N/m^2
		Uniform radial distribution 	• Maxim Displacement: 2,65 mm • Von Mises Stress: ($1{,}12*10^4$... $4{,}24*10^6$) N/m^2 • Principal Tensions: (– $1{,}03*10^6$ ... $6{,}45*10^5$)N/m^2

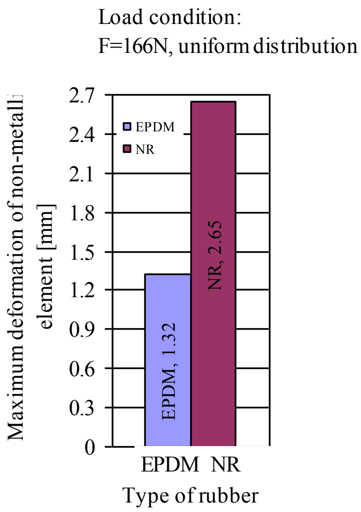


Fig.16. The maxim deformation of shape for uniform radial distribution of applied force

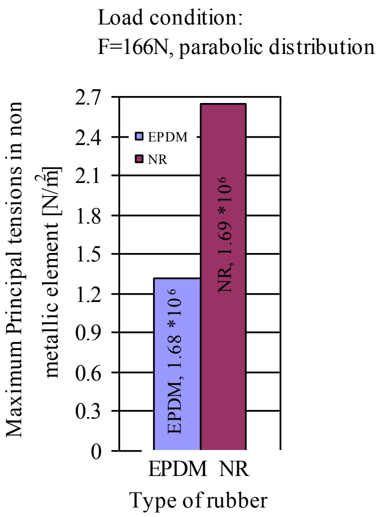


Fig.18. The maximum principal tensions in the non-metallic element for parabolic distribution of applied force

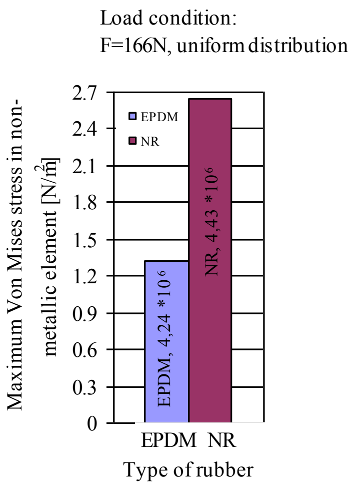


Fig.17. The maxim Von Mises stress in the non-metallic element for uniform radial distribution of applied force

4. CONCLUSION

The analysis using the finite element method of the non-metallic elastic element in the construction of the elastic coupling with cylindrical bolts and non-metallic elements was very important. The study revealed the influence of the characteristics of the material applied to the analyzed element on both the deformation state of the element and the stress states of Von Mises, which are interpreted as equivalent stresses that appear in the analyzed element, respectively on the main stresses.

In the finite element modeling of the nonmetallic element an analysis was performed on different materials, with different mechanical characteristics, different limit conditions and analyzes were performed for the same values of the load force, but different force distribution and the following conclusions were reached. :

➢ by imposing different limit and loading conditions, but also with different characteristics of the material applied non-metallic element, it is established that by changing the limit conditions, the deformation of the non-metallic element decreases;

- by applying a uniform pressure distributed on the inner circular surface of the analyzed element, the force corresponding to the theoretically capable torsion moment, with the increase of the Young modulus of the applied material, a decrease of the deformed element of the analyzed element is established. of natural rubber and uniform force distribution;
- the maximum deformation of the non-metallic element is maximum in the case of the non-metallic element made of natural rubber NR, which means that this element made by NR is more elastic;
- Von Mises stresses have maximum values for the non-metallic element made of Ethylene propylene rubber (EPDM);
- the main stresses that appear in the non-metallic element analyzed for 2 rubber qualities and for limit conditions and imposed loading conditions, have maximum values, having a variation between - 2.02 * 10^6 ... 1.69 * 10^6N / mm^2, values corresponding to the analyzed element with the characteristics of the material corresponding to natural rubber NR.

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REFERENCES

[1] Drăghici, I. et al.: *Calculation and construction of couplings*, Technical Publishing House, Bucharest, 1978

[2] Drăghici, I., et. al.: *Design guide in machine building*, *vol. II*, Technical Publishing House, Bucharest, 1982

[3] Drăghici, I., et. al.: *Combinatorial systematization of couplings with simple functions*, In: Bulletin of the University of Brasov, series A / I, Applied Mechanics, vol. XVI, , pp. 249 – 255, Brasov, 1974

[4] Drăghici, I., et. al.: *Machine parts, vol. II,* University of Brasov, Brasov, 1978

[5] Jula, A., et. al.: *Machine parts, vol. I and II,* University of Brasov, Brasov, 1986

[6] Jula, A., Lateş, M.: *Machine parts,* University of Brasov Publishing House, Brasov, 2004

[7] Jula, A., et. al.: *Machine parts and mechanical transmissions,* Transilvania University of Brasov Publishing House, Brasov, 2005

[8] Catia®Software Corporation. Catia® Version 5 R21 Copyright © Dassault Systems

[9] Mogan, Gh.L: *Finite elements Method in engineering – practice applications*, Lux Libris Publishing, Brasov, 1997

[10] Mogan, Gh.L: *Finite elements Method in engineering–theoretic bases*. Lux Libris Publishing, Brasov, 1999

[11] Radu, M., et. al.: A new elastic coupling with nonmetallic elements, *Proceedings of IX International Conference on Mechanisms and Mechanical Transmissions,* 10 -12 June, Acta Technica Napocensis Publishing House Cluj – Napoca, pp. 167-172, ISSN 1221-5872, 2004

[12] Radu, M.: *Theoretical and experimental studies concerning couplings with non-metallic elastic elements*, Doctoral thesis, Transilvania University of Brasov, 2005

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RESEARCH OF ADHESIVE AL-SHEET JOINTS IN THE DEVELOPMENT OF LIGHTWEIGHT STRUCTURES

Biljana MARKOVIĆ
Aleksija ĐURIĆ
Marija PERENDIJA

Abstract: *Gluing (adhesive joint), as a way of making joints in mechanical engineering, is gaining importance in the development of spacecraft and aircraft, as well as the automotive industry. This requires high load-bearing capacity and stiffness, with minimal weight, so alloys such as aluminum and titanium are used. Adhesive joining is increasingly displacing the dominant rivets when joining light metals, and is used to join thin sheets made of different types of materials. In this paper, the possibilities of adhesive joining and the characteristics of adhesive joints made of aluminum alloy AW-5754 were researched, using static tests, and their fractography was analyzed.*

Keywords : *adhesive joints, light constructions, static testing, Al alloys*

1. INTRODUCTION

In order to increase energy efficiency, the concept of sustainable lightweight (LW) design has been used for the last few years. This concept of lightweight design, which is currently used, refers to the reduction of the weight of the structure by using lighter materials, which include aluminum. The choice of materials for light constructions also means the choice of joining technology, which is of essential importance [1].
In order to think in the right direction when designing and constructing light structures, the prerequisites are the properties of the material such as: stiffness, strength, ability to absorb energy. Usage the maximum potentials of high-performance materials allows choosing the right way to connect them [2].
Adhesion is a major element of the bonding technologies used today [3-5]. This way of joining meets the requirements of mechanical load, with high reliability of the product, and in connection with the production and climatic conditions.
Adhesives used to achieve adhesion must be resistant to crash at high loads, allow uniform application of adequate force, stress distribution, weight reduction and allow better rigidity of components, durability, as well as properties shown in the crash test. In addition, these types of adhesives have advantages that are reflected in low thermal impact on materials, the ability to damping vibrations and to improve sealing [1].
Adhesion is the process of making inseparable bonds in mechanical engineering with non-metallic material, through adhesion and cohesion forces, without significant impact on the structure of the parts to be joined (Figure 1). Adhesion is a state in which two different surfaces made of different (or the same) materials are held together by the interaction of attractive forces due to the interaction of molecules, atoms or ions.
Cohesion or internal strength is the action between two surfaces of a material, ie. attractive forces of identical atoms or molecules. Cohesion strength depends on the material and temperature. Metals have the highest cohesive strength, and liquids and gases have the lowest. The molecular weight of the polymer is an important factor in determining the cohesion strength of the adhesive.
Double action of optimal adhesion and cohesion is required to connect the forces and to achieve the optimal strength of the adhesive joint. When optimal adhesion forces are achieved in the preparation of the bonding material, then the cohesive strength of the bonded joint is the decisive criterion for its strength [6].

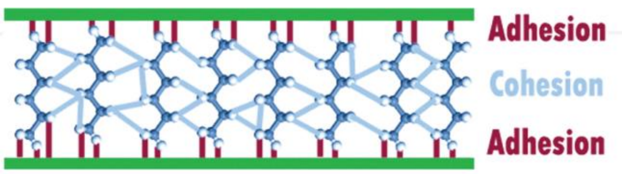

Fig. 1 Adhesion and cohesion bonds in adhesive joint [7]

The mechanisms of adhesion have been intensively researched in recent years; so many theories have been put forward that explain the principles of adhesion.
However, none of them fully explain adhesion. It can be concluded that the adhesion of the adhesive to the surface

of the part to be bonded is the result of mechanical, physical and chemical forces that overlap and affect each other.
After Fe (iron), aluminum is the second metal used in modern mechanical engineering. It is used as a pure metal in electrical engineering, metal processing, food and chemical industries, but its application is much more important in the form of various multicomponent alloys that are widely used in the mechanical industry [8-10]. Joining of aluminum sheets can be achieved by applying the following technologies [3-5, 11, 12]:
- Welding;
- Connection with mechanical elements (screws, rivets);
- Gluing (adhesive bonding);
- Hybrid merger.

Adhesion, due to its low specific weight, as well as due to the thin layer of adhesive in the joints, has an advantage over welded and mechanical joints [13]. Aluminum and its alloys are characterized by extraordinary mechanical properties, which have opened many technological sectors. Although they are much lighter than other metals, they have a very high mechanical strength, which is why they are widely used in the aerospace industry (50%, 68%, depending on the manufacturer and model of the aircraft). It is considered that aluminum constructions can be competitive in applications where low specific weight, corrosion resistance, functionality of construction forms and profiles are important.
In this paper, the analysis of the mechanical properties of the adhesive joint of aluminum alloy AW 5754 with a thickness of 1 mm will be presented. Commercial adhesive, Loctite EA 3430, Henkel, (two-component epoxy adhesive) was used for adhesion.

2. DESIGN OF ADHESIVE JOINTS

The rules for forming adhesive joints are similar to those for solder joints. However, adhesive technology is more complicated and error-prone. The choice of adhesive largely depends on the type of material to be joined, the required joint strength, external influences (humidity, temperature, corrosion) [14].
The possibility of fast and reliable adhesion of all types of materials is the reason why today adhesives are considered a standard part of many production processes. Almost all types of materials such as steel, aluminum, synthetic and composite materials, glass and ceramics can be combined with the help of adhesives. In this way, manufacturers can choose materials without restrictions related to joining different materials [15].

- The decisive role, however, is played by the position of the sheets to be joined, with the appropriate parameters of the manufacturer, which relate to the choice of adhesive. E.g [13]:
- Butt joints are undesirable, pipe butt joints are particularly unfavorable, folding joints with beveled edges are more favorable;
- Angle joints cause stress concentration, so they need to be strengthened at the ends;
- In order to avoid stress concentration, the shear load is the most favorable;

The strength of the adhesive joint depends not only on the correct choice of adhesive, but also on a number of other factors. Thus, numerous tests have shown that in addition to the type of adhesive (including correctly implemented adhesive technology), environmental conditions, temperature, duration of load, type of load, surface treatment, etc. are also influential.
Adhesive joints are subject to changes in mechanical properties, depending on the time elapsed in operation regardless of the load (the so-called aging effect of the adhesive). This effect occurs even without load, after long-term storage of the joined elements. The aging of metal adhesives depends primarily on the type of adhesive, the condition of the surfaces before adhesion, but mostly on the environment in which the bond is glued (dry air or sea water). Resistance against aging is generally higher with hot-setting adhesives than with cold-setting adhesives [16, 17]. The thickness of the adhesive layer in the bonded joint also affects the strength of the joint. It is always more advantageous that the thickness of the adhesive layer is smaller. An adhesive layer thickness of 0.05 to 0.15 mm is considered optimal for most adhesives [18]. This is all true for folding and butt joints of sheets and similar shapes, where it is relatively difficult to control the thickness of the adhesive layer. Otherwise, the exact thickness of the adhesive layer can be achieved only by connecting pipes and similar elements with a closed contour.
Surface treatment significantly affects the strength of the adhesive joints of aluminum alloys. Yasmin Boutar et al [19] founded that the decrease in surface roughness was found to increase the shear strength of single lap joints. Experimental results show that rougher surfaces have less wettability which is in coherent with shear strength tests. The author's C. Borsellino et al [20] also conclude that roughness significantly affects the strength of the adhesive joints of aluminum alloys.
The strength of the adhesive joints is highly temperature dependent [21], with cold binder adhesives being more sensitive to temperature rise than hot binders. Hot-melt adhesives are used for temperatures up to about 250ºC (there are also special high-temperature adhesives up to 350ºC), so that the maximum allowable permanent temperature of the loaded adhesive joint (excluding other influences) is determined by these values.

3. TESTING OF ADHESIVE JOINTS

The failure mode of the adhesive joint depends on a number of factors: adhesive properties (cohesion and adhesion strength), bonding material properties (free surface energy, surface roughness, surface cleanliness, mechanical properties), adhesion process and flow, pressure, temperature, time, humidity etc.), the design of the adhesive joint (adhesive layer thickness, substrate thickness, joint types and dimensions) and load conditions (load type-static or dynamic: mode, time, temperatures, loads, etc.).
Adhesive joints should be shaped so that they are primarily shear stress (folding joint) and to a lesser extent tension / pressure (butt joint), therefore, in these joints the working force should act in the plane where the joint is

made. Bending and twisting stresses should be avoided [14].
Testing of adhesive joints involves static and dynamic testing. Adhesive joints are tested in the following three ways [22]: a tensile-shear test known as the TS test (Figure 2a); L tensile test (Fig. 2b); H tensile test (Figure 2c).

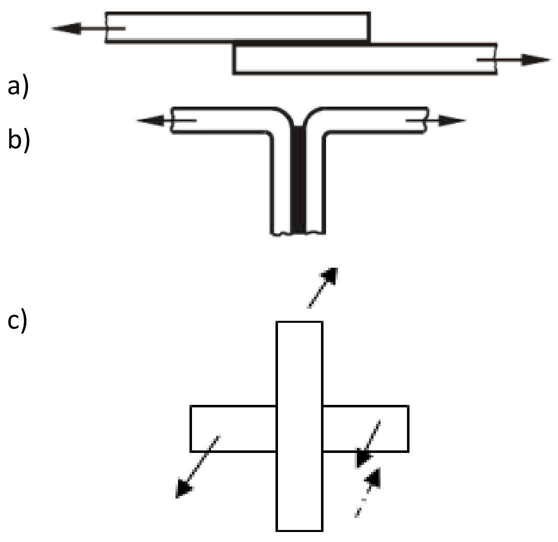

Fig. 2 Methods for testing the adhesive joint: a) TS test; b) L test; c) CT test

The values of the degree of safety of the adhesive joint is in the range S=2-5. The most important influencing factors on the load-bearing capacity of adhesive joints are the type of material to be joined, the thickness of the adhesive in the joint, the roughness of the adhesive joints surfaces, the environment during operation and similar.
Different types of fractures can occur during tensile testing. Four types of fractures are characteristic for an adhesive joint [23]:

1. Adhesive fracture (Fig. 3 a);
2. Adhesive-cohesive fracture (Fig 3 b);
3. Cohesive fracture (Fig 3 c);
4. Subtractive fracture (Fig 3 d).

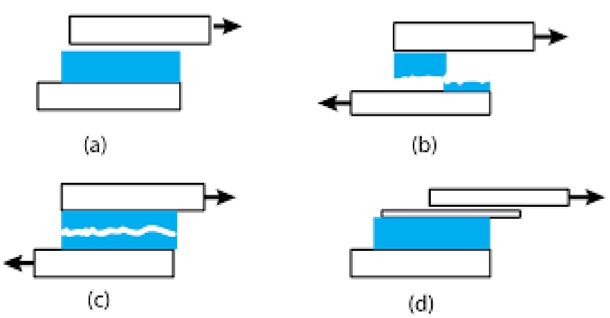

Fig 3.Types of fracture in adhesive joints [23]

4. EXPERIMENTAL RESERACH

The test was adjusted to the equipment of the Faculty of Mechanical Engineering of the University of East Sarajevo (SHIMADZU AGS-X test machine). Tension-shear test was performed, i.e. TS test. The speed of the traverse during the test was 2 [mm/min]. The aim of the test is to determine the maximum force that the adhesive joint can withstand. The test was done for three samples.
Preparation of test specimens was performed in accordance with available research, experientially sheet thickness 1mm (Figure 4). Cutting and bending of the samples was done by hand with the use of auxiliary tools. The first sanding was performed with P120 sandpaper, and the final sanding with P240 granulation paper. At the end of grinding, the samples were cleaned with alcohol, Ethanol 96%. This is a common process of preparing samples for adhesion and the goal of sanding and cleaning is to remove impurities from the metal surface that can affect the quality of the joint.

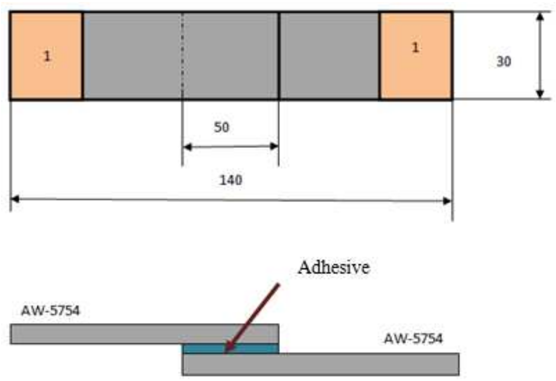

Fig. 4. Prepared samples for adhesion

The samples were adhesived with Loctite EA 3430 (Henkel). It is a two-component epoxy adhesive that has great application in industry. Adhesion time was 10 minutes, taking into account the viscosity of the adhesive.
After the adhesion process, the samples were clamped with plastic clamps to prevent movement during the drying process. The drying process lasted 24 hours at room temperature (approximately 20 °C).

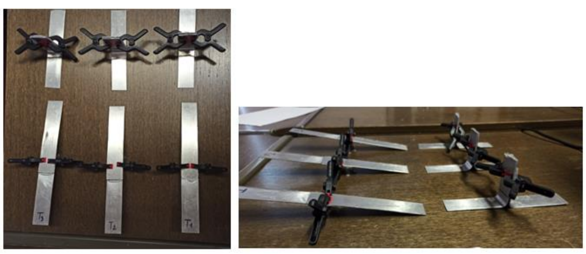

Fig. 5. Samples during drying

The results of the tensile test (TS test) are shown in Figures 6, 7, 8.

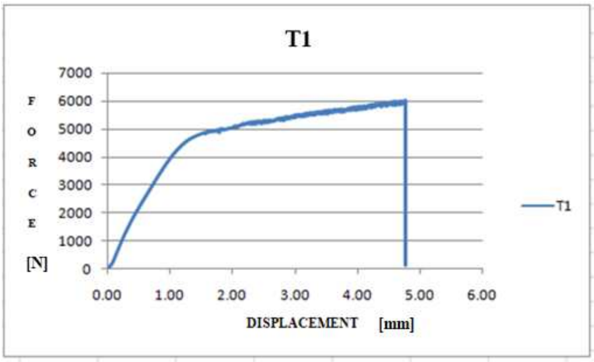

Fig. 6. Force- displacement diagram for sample T1

The figures show that the adhesive joint withstood a force in the range of 6000-6500 N. Taking into account the thickness of aluminum alloy sheets AW-5754, which is 1 mm, and width 30 mm, and tensile strength Rm = 245 N/mm2 it is concluded that sheet metal of these dimensions and this material can withstand a force of approximately 7350 N. Comparing this value with the value obtained in the tensile test, it can be concluded that the given joint gives satisfactory mechanical characteristics because the load-bearing capacity of the base material (sample) is only 11% higher than the load-bearing capacity of the adhesive joint.

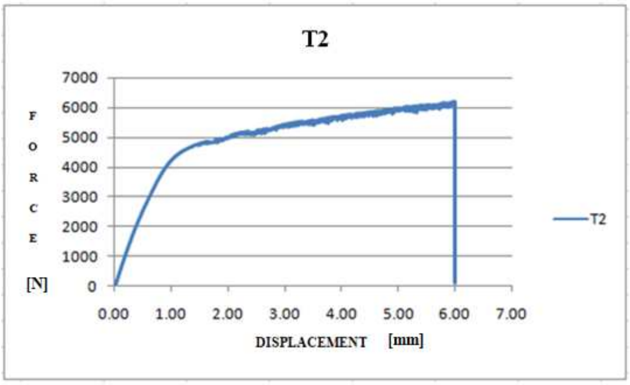

Fig. 7. Force-displacement diagram for sample T2

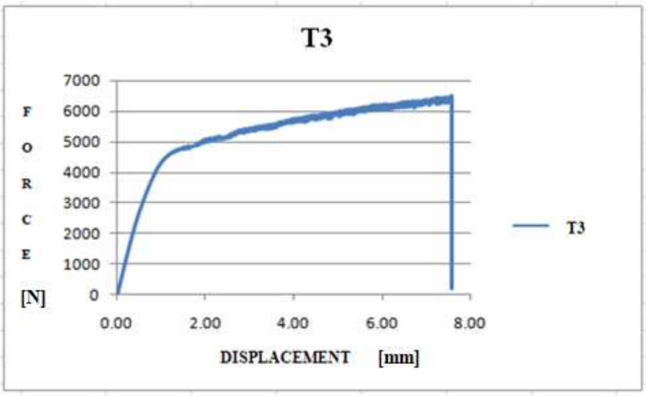

Fig. 8. Force- displacement diagram for sample T3

In all three diagrams, it can be noticed that when the moment the force reaches approximately 4000 N, a zigzag line appears, which manifests itself from the occasional tearing (cracking) of the adhesive.

Figure 9 shows the T (T1, T2, T3) samples after fracture, while Figures 10, 11, 12 show the fractography of the compound.

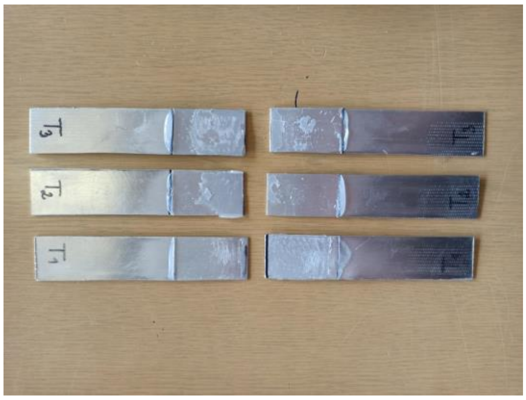

Fig. 9. Display of T samples after fracture

Fractography of the joins was performed on a Leica EZ4 microscope, and from the analysis of the result it can be concluded that in these cases there is an adhesive-cohesive fracture.

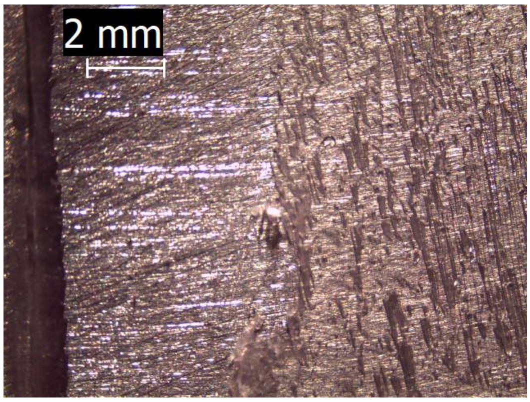

Fig. 10. Fractography of the T1 join sample

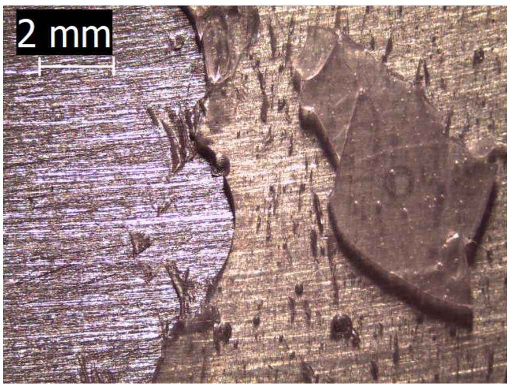

Fig. 11. Fractography of the T2 join sample

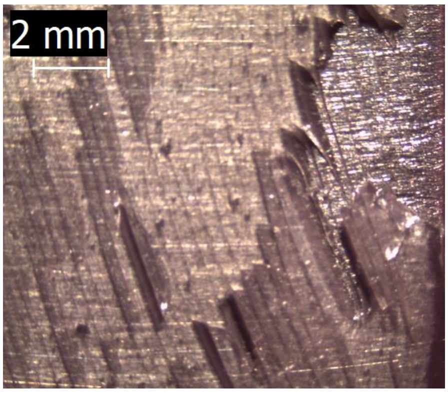

Fig. 12. Fractography of the T3 join sample

5. CONCLUSION

Considering the trend of design development for lightweight structures and the requirements for high productivity in industrial production, the increased use of structural adhesives is expected. Mentioned adhesives will be more and more represented, because the design focused on lightweight constructions means saving resources, and this is impossible to achieve, among other things, without the use of adhesives. There is a clear trend of increasing use of composite materials and aluminum alloys, primarily in the automotive and aerospace industries because weight reduction is very important in these industries. In the future, the success of metalworking companies will largely depend on their ability to exploit the innovative potential of using composite materials. In this sense, structural adhesion is an important factor and key technology (industrial production) in choosing the way of joining in the machine industry, both homogeneous and heterogeneous materials, 21st century. Adhesion is most often used for joining dissimilar materials, but in this paper, joining of homogeneous materials is presented.

Cohesion and adhesion forces are responsible for the strength of the adhesive joint. Although many mechanisms are known to work in the adhesive material and between the adhesive and the surface of the parts to be joined by adhesion, it is still not possible to determine exactly which mechanism is most responsible for creating the adhesive joint, i.e. which mechanism achieves the highest joint strength.

The procedure for adhesion of aluminum alloy sheets AW-5754 is presented and analyzed. Loctite EA 3430 epoxy two-component adhesive from Henkel was used for adhesion. Testing of previously prepared samples was performed using test, namely, the tensile-shear test TS. The test results show that specimens prepared and tested for tensile-shear or TS test can withstand a force in the range of 6000-6500 N. Analyzing the fractography of the joint samples tested by TS test, it can be concluded that adhesive-cohesive fracture has occurred.

The results of the performed experiment are satisfactory from the aspect of durability of the adhesive joint.

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REFERENCES

[1] Ickert L., Adhesive technology – Key to future of lightweight design?. Adhes Adhes Sealants 9, pp. 49–53, 2012.

[2] Meschut, G., Janzen, V., Olfermann, T. Innovative and Highly Productive Joining Technologies for Multi-Material Lightweight Car Body Structures. J. of Materi Eng and Perform 23, pp. 1515–1523, 2014.

[3] Junya, N., Reiichi, S. Multi-material Automotive Bodies and Dissimilar Joining Technology to Realize Multi-material, Kobelco technology review, No. 38, pp. 32-37, 2020.

[4] Ji, H. K., Lyang, S. W., Kaushalya. P., Payam. H., Jami. J. S., Pete, E. Knowledge based design advisory system for multi-material joining, Journal of Manufacturing Systems, Vo. 52, Part B, ISSN 0278-6125, pp. 253-263, 2019.

[5] Delzendehrooy, F., Akhavan-Safar, A., Barbosa, A.Q., Beygi, R., Cardoso, D., Carbas, R.J.C., Marques, E.A.S., Da Silva, L.F.M. A comprehensive review on structural joining techniques in the marine industry, Composite Structures, V. 289, ISSN 0263-8223, 2022.

[6] Bujanis B., Magdalenis Bujanis J., Mehanizmi stvaranja ljepljenog spoja, Technical Gazette, Vo. 5, No. 2, ISSN 1864-6168, pp. 89-93, 2011.

[7] Zotti, A. , Zuppolini, S. , Zarrelli, M. , Anna Borriello, A. . Fracture Toughening Mechanisms in Epoxy Adhesives. In: Rudawska, A., editor. Adhesives - Applications and Properties, London: IntechOpen. 2016.

[8] Hirsch, J. Aluminium in Innovative Light-Weight Car Design, Materials Transactions, Vol. 52, No. 5 pp. 818- 824, 2011.

[9] Udoye, N. E., Inegbenebor, A. O., Fayomi, O. S. I., The Study on Improvement of Aluminium Alloy for Engineering Application: A Review, International Journal of Mechanical Engineering and Technology, Vol. 10, No. 3, pp. 380-385, 2019.

[10] Rambabu, P., Eswara Prasad, N., Kutumbarao, V.V., Wanhill, R.J.H. Aluminium Alloys for Aerospace Applications. In: Prasad, N., Wanhill, R. (eds) Aerospace Materials and Material Technologies . Indian Institute of Metals Series. Springer, Singapore. 2019.

[11] Richard, R., Paul, K,, Belinga, M,. Jukka, M. Trends in aluminium alloy development and their joining methods, Reviews on Advanced Materials Science, Vol. 44, No. 4, pp. 383-397, 2016.

[12] Barnes, T.A., Pashby, I. R. Joining techniques for aluminium spaceframes used in automobiles: Part II — adhesive bonding and mechanical fasteners, Journal of Materials Processing Technology, Vo. 99, No. 1–3, pp. 72-79, 2000.
[13] EAA Aluminium Automotive Manual – Joining, 9. Adhesive bonding, European Aluminium Association, 2015.
[14] Miltenović, V., Marković, B., Tica, M. Konstrukcuini elementi u mašinogradnji 1, Mašinski fakultet Univerziteta u Istočnom Sarajevu, 2018.
[15] Sarah, K., Cindy, J., Steve, L., Guest, E. Enabling sustainable transportation through joining of dissimilar lightweight materials, MRS Bulletin, Vol. 44, No. 8, pp. 608-612, 2019.
[16] Gerald, D., Richard, A. P. Environmental effects on the ageing of epoxy adhesive joints, International Journal of Adhesion and Adhesives, Vo. 29, No. 1, pp. 77-90, 2009.
[17] Hirulkar, N.S., Jaiswal, P.R., Reis, P.N.B., Ferreira, J.A.M. Effect of hygrothermal aging and cyclic thermal shocks on the mechanical performance of single-lap adhesive joints, International Journal of Adhesion and Adhesives, Vol. 99, 2020.
[18] Rośkowicz, M., Godzimirski, J., Komorek, A., Jasztal, M. The Effect of Adhesive Layer Thickness on Joint Static Strength. Materials, 2021, Vol. 14, No. 6, 1499.
[19] Yasmina, B., Sami, N., Salah, M., Moez, B. S. A. Effect of surface treatment on the shear strength of aluminium adhesive single-lap joints for automotive applications. International Journal of Adhesion and Adhesives, Vol. 67, pp. 38-43, 2016.
[20] Borsellino, C., Di Bella, G., Ruisi, V.F. Adhesive joining of aluminium AA6082: The effects of resin and surface treatment, International Journal of Adhesion & Adhesives, Vol. 29 , pp. 36–44, 2009.
[21] Banea, M.D., Da Silva, L.F.M., Campilho, R.D.S.G. Effect of temperature on the shear strength of aluminium single lap bonded joints for high temperature applications, Journal of Adhesion Science and Technology, Vol. 28, No. 14–15, pp. 1367–1381, 2014.
[22] Abd-El Salam, M. H., Khaliel, J. A., Hassan, H. H. Factors affecting the adhesive force between metallic substrate and carbon black filled rubber composites, Journal of Reinforced Plastics and Composites, Vol. 32, No. 13, pp. 974–986, 2013.
[23] Natu, A. V., Ankit, R. S., Nitinkumar, R. A. Variation of Adhesive Strength in Single Lap Joint (SLJ) with Surface Irregularities. American Journal of Mechanical Engineering, Vol. 7, No. 2, pp. 61-67, 2019.

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BASIS FOR SIMPLIFIED ZIPLINE MODEL ANALYSIS

Tanasije JOJIĆ
Jovan VLADIĆ
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Abstract: *This paper shows the procedure for creating a computational zipline model, as a basis for making an experimental model with adjusted geometric characteristics in relation to the real system. Since it is not possible to satisfy the geometric similarity between all sizes of the real zipline and the experimental zipline model, the model will be formed so that it has the same inclination angle and the same deflection ratio in the loaded and unloaded state. The model will enable the variation of a larger number of types and ropes diameters. The idea is to achieve the ratio of rope deflection in the unloaded and loaded state, such as on a real zipline, with different tensile forces for different dimensions or rope types. The kinematic characteristics can be measured later for the obtained variants. Additionally, the measured characteristics can be compared with the calculated values.*

Keywords: *zipline; model; similitude*

1. INTRODUCTION

This paper presents the development of a reduced zipline model, which will later be used for the validation of the computational model and comparison with the real zipline in accordance with the theory of similitude [1, 2].
In general, it is not possible to make a model in a certain geometric scale. For example, a real zipline has a span of about 1.5 kilometres whereas rope with a diameter of 16 mm was used, [3-5]. The simplified zipline model could be about 5 meters long, and the smallest diameter of the rope that can be found in regular production is about 1 mm. Therefore, the modelling of the zipline was approached, which met the condition that it has a similar angle of inclination, as well as that the ratio of deflection in the loaded and unloaded state of the model is identical to the ratio of deflection on the real zipline.
There is a plan to perform measurements in the future on the model which is described in this paper.
For the real zipline, data for the rolling resistance can be found in the literature for cable cranes and ropeways. However, the mentioned data are valid only for certain relationships (ratio) between the load on trolley and tightening force, as well as between the wheel diameter and the mean diameter of the wheel bearing. Therefore, before comparing the results between real zipline and simplified model analysis, the rolling resistance coefficients should be determined in a specific way which is developed by the authors, but which is not the topic of this paper.

2. MODEL DESCRIPTION

Fig. 1 shows the lower station of the model, on which an aluminium frame (1), a steel rope (2), a redirection pulley (3) and a tension weight (4) can be seen.

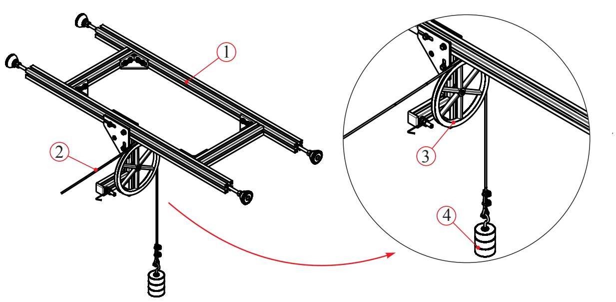

Fig.1. Model of lower station with redirection pulley and tension weight

The experiments are planned to be performed on 6x7 rope construction with a fibre core with a diameter of 2 mm, 3 mm and 4 mm which are shown in Fig. 2.

Fig.2. Wire ropes (left to right 4 mm, 3 mm and 2 mm)

The redirection pulley is made by 3D printing to have as little mass and moment of inertia as possible, and thus have minimal impact when starting. In order to ignore the friction in the redirection pulley bearings, the ratio of the mean bearing diameter and the nominal redirection pulley diameter must be greater than 10. The nominal rope diameter is adopted to be 160 mm, while the outer bearing diameter is 8 mm and the inner 3 mm. The mean diameter of the bearings, in that case, is:

$$d_{mean} = \frac{d_{outer} + d_{inner}}{2} = \frac{8+3}{2} = 5.5 \text{ mm} \tag{1}$$

so the mentioned ratio is:

$$\frac{D_{pulley}}{d_{mean}} = \frac{160}{5.5} \approx 29 \tag{2}$$

which is enough to ignore the friction in the bearings. The redirection pulley model is shown in Fig. 3.

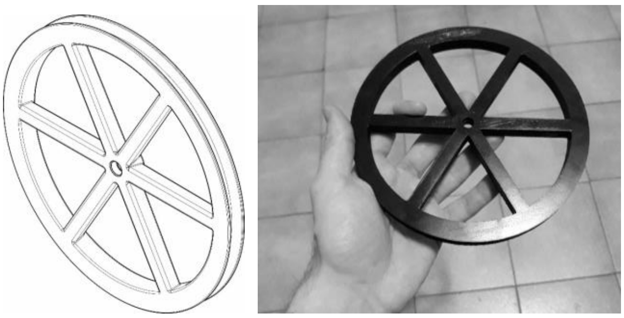

Fig.3. Geometrical model (left) and 3D printed sample (right) of the redirection pulley

Fig. 4 shows the redirection pulley mounted to the lower station and tensioned with weight.

Fig.4. Redirection pulley mounted to the lower station

Fig. 5 shows bearings for the redirection pulley and trolley wheel as well as rope fastener clamps and thimbles.

Fig.5. Bearings for redirection pulley and trolley wheel (left) and rope fastener clamp and thimble (right)

Fig.6. Geometrical model and fabricated sample of wheels

The geometric model and appearance of the 3D printed sample of wheel are shown in Fig. 6, while the geometric model and appearance of the trolley can be seen in Fig. 7. The trolley wheel (Fig. 7, pos. 2), like the redirection

pulley, was obtained by the 3D printing process. The wheel has an outer diameter of 26 mm and a rolling diameter of 16 mm. Identical bearings are installed in the wheel as in the redirection pulley, which means ø8 mm / ø3 mm / 4 mm.
The frame of the trolley (Fig. 7, pos.1) is made of a rectangular aluminium tube in which a threaded rod (Fig. 7, pos. 3) is attached from below, on which a part of the measuring equipment is attached and, if necessary, additional weight. The total weight of the empty trolley is 29 g.

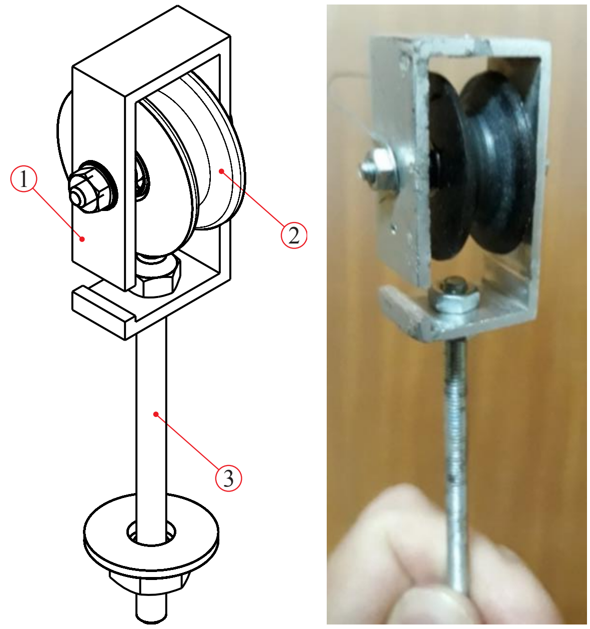

Fig.7. Geometrical model (left) and fabricated sample (right) of the trolley

3. MEASUREMENT PROCEDURE

Measurements were performed using Arduino UNO and Arduino MEGA microcontrollers and appropriate sensors.

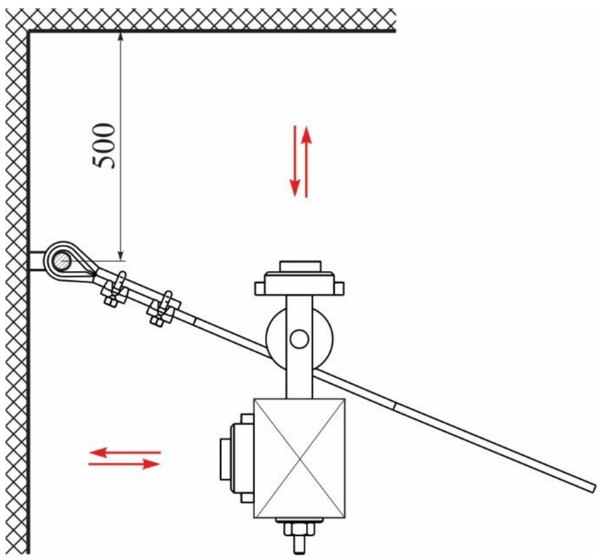

Fig.8. The starting position of the trolley with measuring equipment in the "upper station"

Distances were measured from the wall to which the upper end of the rope was attached, as well as from the ceiling, and the measured values were either recorded on the SD card or sent by radio from the controller which was mounted on the trolley to the controller which was connected to the computer.

3.1. Swinging issues

The centre of gravity of the trolley is not at the centre of the wheel but is lowered relative to it. So, if the trolley is not released from the position where the centre of gravity is exactly vertically below the point of contact between the wheel and rope, swinging will occur during movement. The swinging also occurs as a consequence of the "delay" of the load about the trolley in the initial moments of movement. The mentioned swinging, if it is within some reasonable limits (the one that occurs due to the "delay" of the load with a possible small imbalance during release) does not have a great impact on the range and maximum speed. In order to substantiate this claim, the following diagrams of travelled distance and change of velocity over time for cases where the load is suspended as a mathematical pendulum and for the case when the mass of the load is concentrated in the centre of the trolley wheel are given. To maximize the impact of the swing, damping and friction between the connecting rod and the trolley have been neglected.

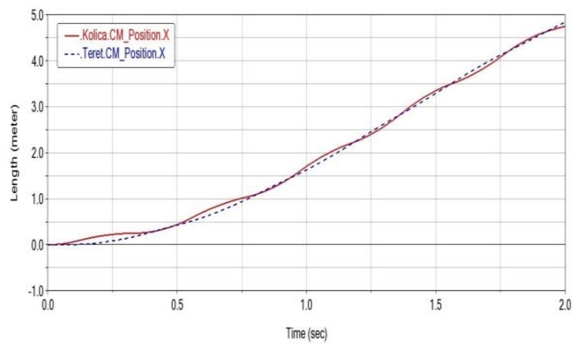

Fig.9. Diagram of range for trolley and load in case when the load is modelled as a mathematical pendulum

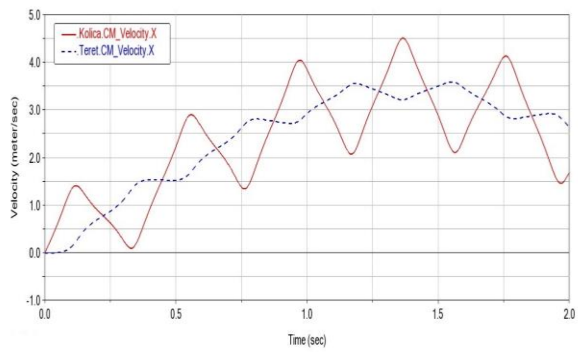

Fig.10. Diagram of velocity for trolley and load in case when the load is modelled as a mathematical pendulum

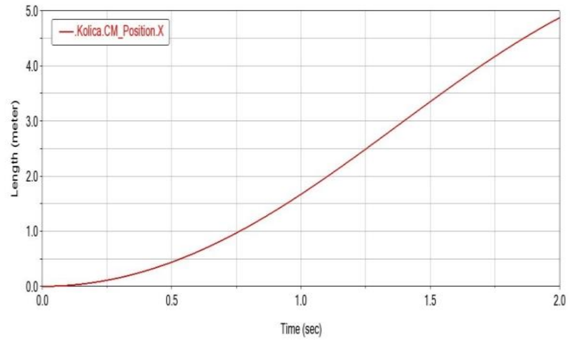

Fig.11. Diagram of range in case when the mass of the load is concentrated in the trolley wheel centre

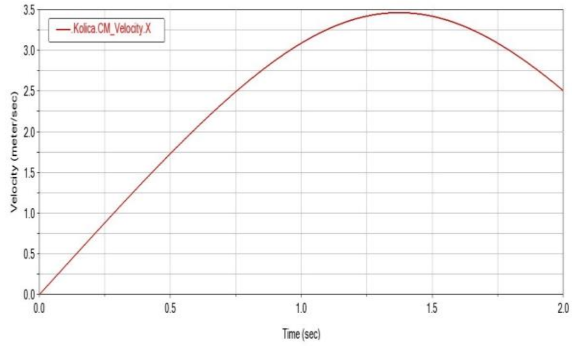

Fig.12. Diagram of velocity in case when the mass of the load is concentrated in the trolley wheel centre

Swinging has a much greater impact on the measurements than on the driving characteristics themselves. Namely, although the velocity oscillates around a certain value, the final range is practically the same as when observing the movement of a material point. However, a problem arises when reading sensor values. The first, bigger, problem arises due to the fact that the returning ray can pass the sensor. Another, and much smaller, problem lies in the fact that instead of the sensors giving the shortest distance from them to the wall or ceiling, they actually give the slanting distance. This problem could be solved by using a gyroscope that would give a value of angle at a certain point, so that the real distances could be recalculated.

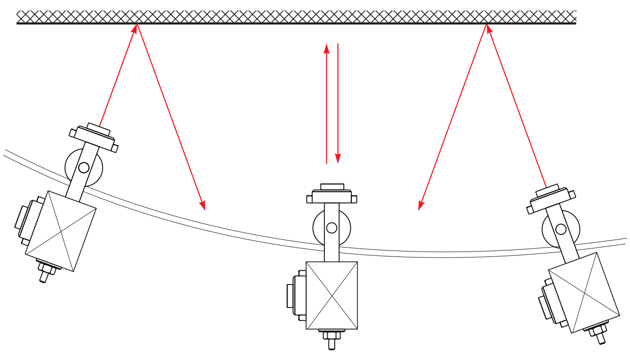

Fig.13. Passing of returning ray and receiving zone of the sensor due to load swinging

The swinging is most expressive after the stopping of the trolley, but those do not affect the driving characteristics.

3.2. Ultrasonic sensor issues

The ultrasonic sensor works by sending a specific signal and waiting for the rejected sound to return. The sensor is in principle intended for measuring distances in quasi-static conditions, [8]. The sensor that measures the horizontal distance has a problem due to the Doppler effect.

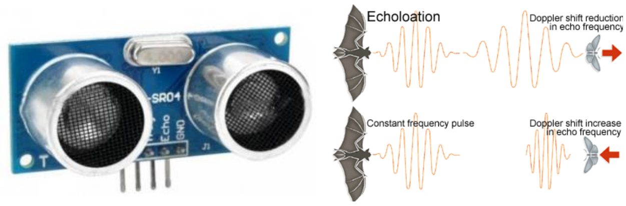

Fig.14. Ultrasonic sensor (left) and Doppler effect (right)

Sensor intended for measuring the vertical distance has a problem that, due to the high speed of the trolley in the horizontal direction, the feedback signal passes the sensor.

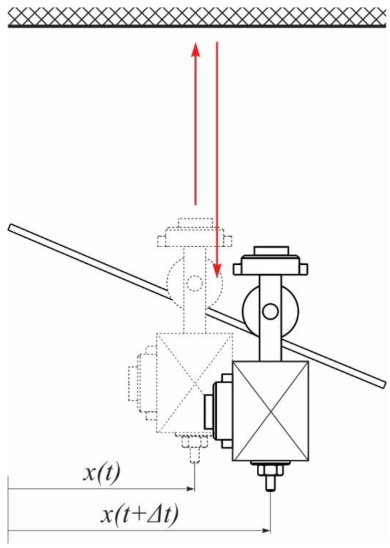

Fig.15. Inappropriate velocity

For example, the distance of the upper point of hanging the rope from the ceiling is 50 cm, while the maximum deflection in case of a rope with a diameter of 3 mm with span of 4.7 m and a drop of 0.4 m tightened with a weight of 500 g for lowering of the trolley with measuring equipment weighing 185 g is 46 cm measured in relation to the lower station. This gives the greatest possible distance from the vertical sensor to the ceiling of 136 cm. If it is assumed that the speed of the trolley in the horizontal direction of 3 m/s can occur, it means that the sound emitted from the vertical sensor would be necessary:

$$t = \frac{s_{vert}}{v_{air}} = \frac{2 \cdot 1.36}{340} = 0.008 \text{ s} \tag{3}$$

to reach the ceiling and go back. During that time, the trolley would move:

$$s_{hor} = v_{hor} \cdot t = 3 \cdot 0.008 = 0.024 \text{ m=24 mm} \tag{4}$$

in the horizontal direction, which is too much for given size of the sensor receiving zone which amounts 16 mm. The second problem, which is expressed in the sensor that measures the horizontal distance, arises due to the relatively wide “measuring angle” due to which the rope gets into the measuring zone.

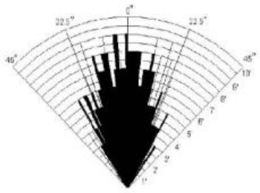

Fig.16. Width of measuring zone, [8]

The problem was partially reduced by using rectifiers mounted on the emitter of the horizontal sensor. Fig. 17 shows the propagation of an ultrasonic wave for the case with and without a rectifier.

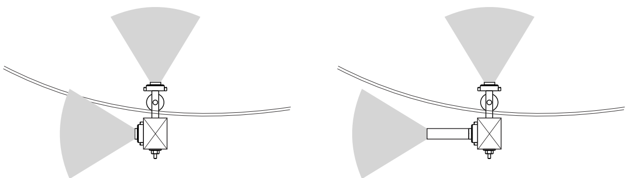

Fig.17. Propagation of an ultrasonic wave for the case with (right) and without a rectifier (left)

3.3. LiDAR sensor

The LiDAR laser sensor works on a similar principle as the ultrasonic sensor, but with the emission of a light ray instead of ultrasound.

Fig.18. LiDAR sensor

Fig. 19 shows a model of a trolley with measuring equipment. The figure shows only the basic layout where the wires are omitted for clarity.

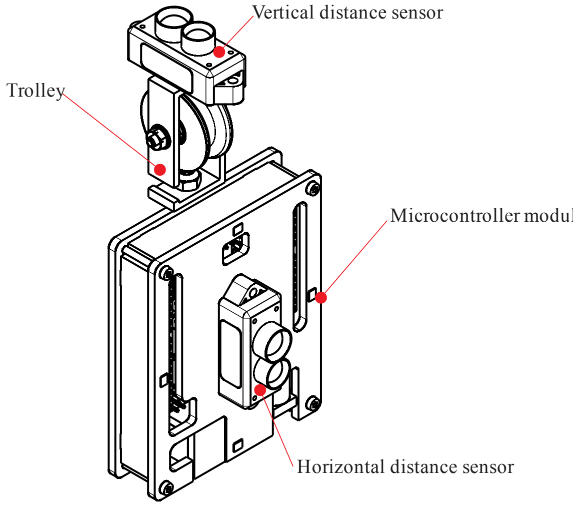

Fig.19. Trolley with measuring equipment

As already mentioned, the problems described in the previous point can be avoided by using a laser sensor. Namely, the laser sensor has a significantly narrower “measuring angle” which for the specifically selected LiDAR TF Mini model is 2.30 degrees, [9]. As the ray is emitted at the speed of light, there is no problem with the Doppler effect and bypassing of the returning ray and the sensor.

4. CONCLUSION

Within the paper, a simplified model of zipline was described.
Since the mentioned scaled model wants to achieve model similarity, some quantities can be recalculated, but not all of them. For those which can not be recalculated, a procedure for their determination must be developed.
Paper gives also a measurement procedure. The load swinging problem is analyzed and conditions under which it could be neglected are given. Issues whit some kind of sensors like ultrasonic are considered, as well as recommendations for their overcoming.

REFERENCES

[1] Sedov, L. I.: *Similarity and dimensional methods in mechanics*, Russian Academy of Sciences, Moscow, Russia, 1980
[2] Emori, R. I., Schuring, D. J.: *Scale models in engineering*, Pergamon Press, Oxford, United Kingdom, 1977
[3] Vladić, J., Đokić, R., Jojić, T.: *Elaborats I, II and III - Analysis of the zipline system in Vrdnik*, Faculty of Technical Sciences, Novi Sad, Serbia, 2017
[4] Jojić, T., Vladić, J., Đokić, R.: Anchorage type and tension rope force impact on zipline’s kinematic characteristics, *Machine Design*, Vol. 11, No. 4, pp. 149-154, 2019

[5] Vladić, J., Đokić, R., Jojić, T.: Theoretical analysis and determination of zipline movement parameters, *Tehnika*, Vol. 68, No. 3, pp. 405-412, 2019
[6] Oxer, J., Blemings, H.: *Practical Arduino – Cool Projects for Open Source Hardware*, Springer-Verlag, New York, United States of America, 2009
[7] Bayle, J.: *C Programming for Arduino,* Packt Publishing, Birmingham, United Kingdom, 2013
[8] *Product User's Manual – HCSR04 Ultrasonic Sensor*, Cytron Technologies, Skudai, Malaysia
[9] *Product Manual of TFmini*, Benewake, Beijing, People's Republic of China

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VIBRATION ANALYSIS OF THERMAL IMBALANCE OF TURBOGENERATOR ROTOR

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Abstract: *The appearance of an uneven temperature field in the rotor of the turbogenerator occurs due to uneven heating or cooling and due to asymmetric distribution in the structure of the rotor masses. As a consequence of the uneven distribution of the temperature field in the rotor, deformations (thermal deflection) occur, which result in a change in vibration levels and unstable system operation. These deformations are manifested as additional deflections of the rotor, so that the state of balance of the system changes significantly. Vibration analysis and monitoring are one of the most reliable ways to diagnose the existence of thermal deflection. This paper deals with the phenomena of thermal deflection, the appropriate mathematical model is given, and the emphasis is on diagnosing this problem using vibration analysis. It should be noted that the thermal balancing process can be carried out by changing the intensity and location of cooling on the rotor, which is achieved by dampening the flow of coolant. These interventions can be done on the basis of detailed analyzes of the causes in a complex system of heating and cooling of turbogenerators.*

Keywords: *vibration, thermal inbalance, diagnostics, turbogenerators*

1. INTRODUCTION

The appearance of an uneven temperature field in the rotor of the turbogenerator occurs due to uneven heating or cooling and due to asymmetric distribution in the structure of the rotor masses. As a consequence of the uneven distribution of the temperature field in the rotor, its deformations occur, which result in a change in vibration levels and unstable operation of the system. These deformations are manifested as additional deflections of the rotor, so that the state of balance of the system changes significantly. Vibration analysis and monitoring are one of the most reliable ways to diagnose the existence of thermal deflection.

By monitoring the trend of 1X vibration component, due imbalance, comparing with the trend of process parameters (primarily reactive power) the existence of this defect can be diagnosed. Thermal imbalance during stationary operation of the generator causes a change in the amplitude and phase of the 1X vibration component.

The paper deals with the phenomena of thermal deflection, the appropriate mathematical model is given and the emphasis is on diagnosing this defect by vibration analysis. The correctness of this diagnosis was confirmed on the synchronous generator of TPP Gacko (type TBB-320-2).

It should be noted that the thermal balancing process is carried out by changing the intensity and location of cooling on the rotor, which is achieved by dampening the flow of coolant. These interventions can be reported on the basis of detailed analyzes of the causes in the complex heating and cooling system in turbogenerators.

2. FORMAT TEMPERATURE FIELD OF TURBOGENERATOR ROTOR

During the operation of synchronous generators, a large part of energy is lost and converted into heat. Losses consist of losses in the stator and rotor windings, then in the core and losses in bearings and seals where the kinetic energy is converted into heat. The examination revealed empirical dependences of the lost energy converted into heat and other types of energy and power of synchronous generators (Fig. 1).

It should be noted that when changing the mode of operation of the generator and uneven cooling on the rotor circumference due to various possible causes (errors in processing, asymmetry and unevenness of cooling openings and grooves for windings, dust, cracks, etc.) asymmetric and nonstationary temperature fields occur in different locations and has its change in time.

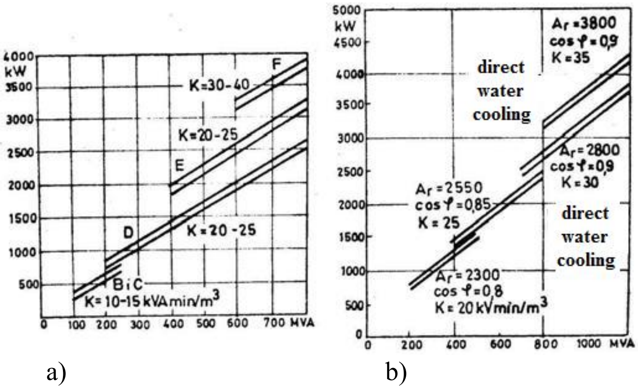

Fig. 1. Losses: a) stator winding, b) in the rotor of synchronous generators depending on power, type of cooling and efficiency factor K

To these losses it should be added another 25% of losses in iron and 20% of losses due to friction in bearings and seals in relation to the losses in Fig. 1a. As most of the lost energy is converted into heat which must be removed from the generator by cooling, another 25% of energy is needed (according to diagram 1a) for cooling the generator [5]. Table 1 shows the type of cooling and the influence of the type of cooling on the efficiency factor K. Fig. 2 shows a schematic cross-section of a synchronous generator with a cooling system. Cooling of rotor and stator grooves with windings is performed with coolant according to Table 1 and the appearance of rotor grooves and possible cooling methods is shown in Fig. 3.

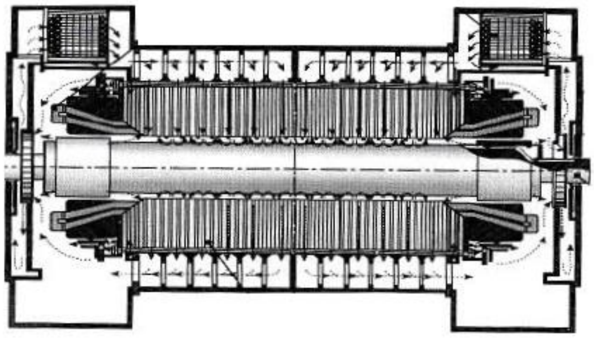

Fig. 2. Schematic display of turbogenerator with cooling system

Table 1.

Cooling		Refrigerant			Power	
stator	rotor	For stator windings	For rotor windings	For stator iron	[MW]	Efficiency factor K [kVA min/m^3]
indirectly	indirectly	air	air	air	100	-
indirectly	indirectly	hydrogen	hydrogen	hydrogen	320	11
indirectly	directly	hydrogen	hydrogen	hydrogen	500	17,5
directly	directly	hydrogen	hydrogen	hydrogen	800	28
directly	directly	water	hydrogen	hydrogen	800	28
directly	directly	water	water	water, air	1200	42

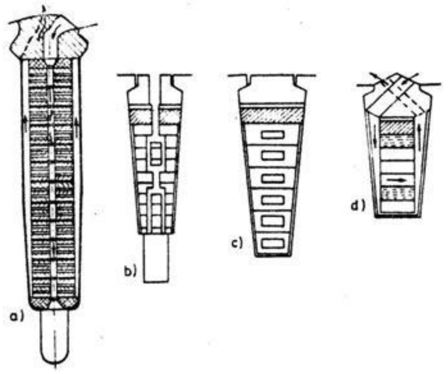

Fig.3. Schematic display of grooves shape and cooling type

Due to such, even very small temperature differences due to the high elasticity of the rotor and the large gap between the bearings, a deflection of the neutral line of the rotor is formed which has the direct consequence of smaller or larger vibrations on the generator bearings. It should be noted that a temperature difference of only 1.5°C can cause a deflection of the elastic rotor line of 0.1 mm. In companies where generators are produced, in such cases the empirical procedure of correcting the flow of coolant in certain zones of the rotor is performed.

3. MATHEMATICAL MODEL OF THE ROTOR IN THE EXISTENCE OF THERMAL DEFLECTION

The mathematical model is oriented towards the detection of this defect by means of the analysis of the sensor response given by the sensors placed in the bearings of the turbogenerator. The model is shown as an elastic rotor with concentric masses. Additional imbalance due to thermal deflection introduces additional inertial force into the model as an external force into the system. Consider a model of an elastic rotor with an asymmetric temperature field, Fig. 4.

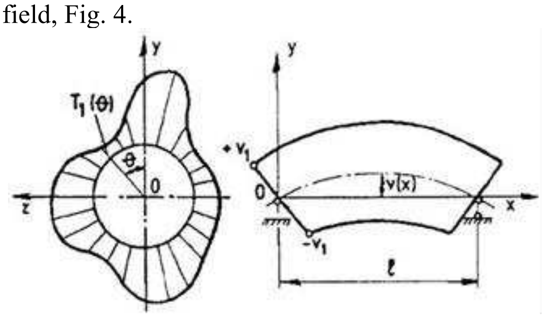

Fig. 4. Schematic representation of asymmetric temperature fields and deformable shape of the rotor

Based on the equations of mathematical physics, for the case of a real model of a turbogenerator, the analytical model of a rotating temperature field can be described by differential equation (1):

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_r \frac{\partial T}{\partial r}\right)+\frac{\lambda\partial^2 T}{r^2\partial\theta^2}+\frac{\partial T}{\partial\theta}\omega\lambda+\frac{\partial^2 T}{\partial x^2}=\rho c\frac{\partial T}{\partial t}+q(r,\theta,x,t) \qquad (1)$$

with boundary condition (Fig. 4):

$T = T_1(\theta)$ for $r = R$ and

$$T(r,\theta)=\sum_{n=0}^{\infty}\left(\frac{r}{R}\right)^n \left(a_n\cos(n\theta)+b_n\sin(n\theta)\right)$$

where temperature field in case of system defined by cylindrical coordinates. In order to define the deflection of the neutral line of the bent rotor, the Bernulli-Euler hypothesis which defines the thermoelastic moments and the deflection of the rotor was used.

In the case of stationary mode, the temperature deviations can be described by differential equations:

$$\frac{d^2V}{dx^2}=-\frac{\alpha a_1}{R},\frac{d^2V}{dx^2}=-\frac{\alpha b_1}{R} \qquad (2)$$

where a1 and b1 are coefficients.

By including the boundary conditions that the deflections on the supports are equal to zero (Fig. 3), and by integrating the differential equations (3), we obtain the expression for the deflection of the neutral line due to thermal deflection:

$$e=\frac{\alpha l x}{d}\left(1-\frac{x}{l}\right)\sqrt{a_1^2+b_1^2} \qquad (3)$$

It is clearly seen that the existence of thermal deflection in the mathematical sense creates an additional imbalance that differs in phase from mechanical, with amplitude and phase change depending on the temperature difference in the rotor structure. Logically, the conclusion follows that the image of rotor balance will change in the vibrational response (change of 1X component amplitude and phase).

The maximum deflection of the neutral rotor line is in the middle of the rotor and has the form:

$$e_{\max}=\frac{l(1+\alpha\Delta T)}{2d\cdot\arcsin\frac{l\alpha\Delta T}{2}}(d-\sqrt{d^2-(l\alpha\Delta T)^2} \qquad (4)$$

Now on the basis of known dependence it is possible to obtain a value for the inertial forces due to thermal imbalance.
By solving differential equation (1), values of temperatures when rotating the rotor are obtained, which affect the intensity of inertial forces. Thus, the inertial force due to thermal imbalance can be analytically expressed as:

$$F_{in}=\int me(r,\theta,x,t,\omega,\Delta T)\omega^2 dx \qquad (5)$$

The overall mathematical model of a multimodal rotor in a fluid environment can be presented and described as follows (Fig. 5):

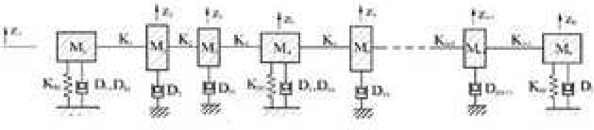

Fig. 5. Model of multimodal rotor with sliding bearings

Differential equations of motion of a multimodal rotor with sliding bearings, where in addition to the mechanical unbalance there is also a thermal unbalance can be written in the form:

$$M_i\ddot{z}_i+D_{si}\dot{z}_i+K_i(z_i-z_{i+1})+K_{i-1}(z_i-z_{i-1})+F_{fli}=$$
$$m_i r_{mi}\omega^2 e^{j(\omega t+\varepsilon_i)}+F_{in}^T \qquad (6)$$
$$i=1,...n; z_1-z_0=0; z_n-z_{n+1}=0$$

4. DIAGNOSISING THE EXISTENCE OF THERMAL DEFLECTION ON THE TURBOGENERATOR ROTOR

The procedure of diagnosing and determining the influence of the thermal field on the dynamic behavior of the rotor will be presented on the example of monitoring and testing of turbogenerators in TPP Gacko. Real-time monitoring of turbogenerator condition showed that the 1X vibration component (amplitude and phase) of rotor vibrations measured near the generator bearings (Fig. 6) changed, which significantly affects the dynamic behavior of the turbogenerator as a whole.

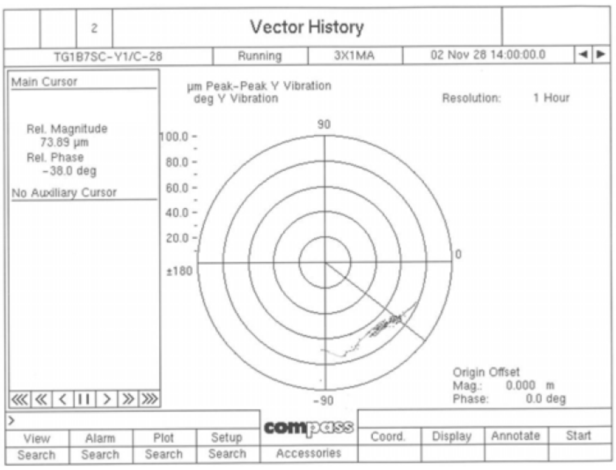

Fig. 6. Trend 1X vibration components of rotor vibrations near bearing L7In this sense the asymmetry of the magnetic field and the existence of thermal deflection on the rotor part of the turbogenerator

The following test program was performed:
- At idle speed, at operating speed, without excitation current, perform vibration analysis of generator bearings and, if possible, rotor shafts on contact rings. Stabilization time regime should be not less than 10-15 min.
- Give the excitation current to the windings at idle rotor generator and record the vibration state of the bearings

generator (determine the effect of magnetic asymmetry fields).

- Synchronize and connect the generator to the network. Raise the load gradually by staying at least at 3 stable operating modes up to full load.The stabilization time of each regime should be minimum 45 min. Record for each mode vibration characteristics of bearings.
- Switch off the drive and record at operating speed vibration characteristics of bearings

It should be noted that the installed online diagnostic system "COMPASS" version 6, which is used to monitor the operation of the unit, was used for testing purposes.

Table 2.

Analysis of rotor vibrations measured in the bearing area 6 and 7 [μm]																		
	Time (19.11.02.)	Number of revolutions	Active power	Reactive power	Bearing 6						Bearing 7					
					V			H			V			H		
			[MW]	[Mvar]	1X	phase 1X	2X	1X	phase 1X	2X	1X	phase 1X	2X	1X	phase 1X	2X
1	17:03	3000	-	-	49,6	-95	22,4	32,9	153	14	28,9	132	29,6	75,9	-84	37,9
2	17:47	3000	given initiative		55,2	-103	22,5	37,8	144	13,9	37,5	116	30,9	75,7	-94	39,6
3	18:42	3000	73	17,7	57,8	-108	26,2	37,8	148	18,3	28,8	113	30	73,1	-94	39,6
4	20:00	3000	274	86	49	-99	25,4	34,8	158	21,2	29,3	118	30,4	72,7	-86,6	36,1
5	21:10	3000	282	91	56	-71	32	32	198	25	29	222	36	89	-10	41
6	21:30	3000	Initiative off		59	-82	31	35	179	25	21	191	34	75	-40	41

The test results are shown in Table 2. In Fig. 7 and 8 polar representations of the trend of 1X rotor vibration vectors measured near generator bearings over time are given. The analysis of the results from the polar diagrams clearly shows the existence of thermal imbalance, as well as the influence of the magnetic field asymmetry on the dynamic behavior of the aggregate as a whole. Vectors of 1X rotor vibrations in different operating modes of the unit are shown: A1-vector of 1X rotor vibrations by going to operating speed, A2-vector 1X with given excitation, A3-vector 1X after synchronization, A4-vector 1X after increase of excitation current, ie reactive power from 17.7 to 91 MW and system stabilization (45 min), A5-vector 1X after disconnection.

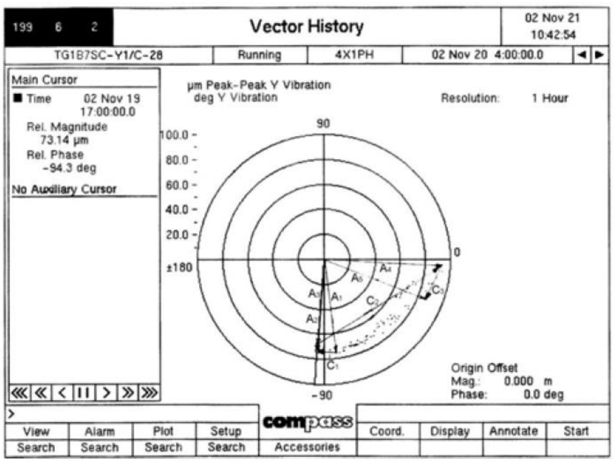

Fig. 7. Polar diagram of 1X vibration component in bearing 7

The influence of thermal imbalance and magnetic field asymmetry on the overall dynamic behavior of the rotor can now be determined. The determined test values are: C1-vector of asymmetry of the magnetic field in the cold state of the rotor, C2-vector of thermal imbalance with 17.7 to 91 MVar, C3-vector of thermal imbalance in the heated rotor. It can be seen that the thermal imbalance at a reactive power of 91 MVar is the same in intensity as the residual mechanical imbalance on the rotor, but that it differs in phase by 45°. Following the trend of further changes in the thermal imbalance vector, it can be concluded that by further increasing the reactive power, the total unbalance vector (vector 1X of rotor vibrations) would be inadmissible for further operation of turbogenerators (especially on bearing 7). So, in the process of further exploitation of the block the reactive power should be limited.

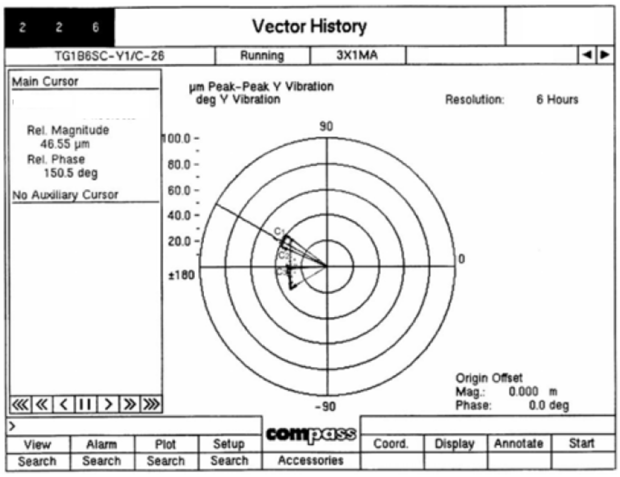

Fig. 8. Polar diagram of 1X vibration component in bearing 6

5. CONCLUSION

This paper deals with the problem of thermal unbalance of synchronous generators. Emphasis is placed on the timely diagnosis of this defect by analyzing vibrations and determining its impact on the dynamic failure of the system as a whole. It has been shown that the best indicator of the existence of thermal deflection is the monitoring of 1X vibration vectors in the production process. The existence of thermal deflection causes a change in the amplitude and phase of this vector. However, such a change in the 1X vibration vector can be a consequence of other defects in the system (looseness of rotating parts, contact of the rotor on the stator due to increased mechanical deflection, propagation of cracks in the rotor or foundations, etc.). Thus, to determine the existence of this defect, a specific test program should be performed (Chapter 3). After determining the existence of thermal deflection, vibrodiagnostic analysis can determine its effect on the overall dynamic behavior of the system and clearly predict side effects. If it is determined that in the production process the process parameters will be in the zone where they will cause asymmetry of the temperature field of the rotor that causes inadmissible deflection, it must be resorted to its elimination. Note that the elimination of this problem cannot be solved by mechanical correction of the rotating masses of the rotor, but the intervention of thermal balancing must be resorted to.

6. SYMBOLS AND NOTATION

T -temperature, t - time,
r,θ , x - cylinrical coordinates,
λ - thermal conductivity
coefficient, ω – angular velocity,
ρ - density,
c - specific heat,
q - amount of heat,
e - eccentricity of the rotor mass center from the axis of rotation,
$z_i = x_i + jy_i$ - radial rotor displacement in fixed coordinates
α - coefficient of linear expansion,
l- rotor length,
M_i -modal mass,
K_i -modal stiffness,
D_{si} - modal damping of the rotor environment,
m_i - unbalanced mass,
r_{mi} - imbalance radius,
ε_i - unbalance mass angle,
F_{in}^T - inertial force due to thermal imbalance,
V, W- deflections of the neutral rotor line in the horizontal or vertical direction,
R,d- radius or rotor diameter.

REFERENCES

[1] Muszynska, A.: Vibrational Diagnostics of Rotating Machinery Malfunctions, *International Jurnal of Rotating Machinery*, Vol. 1, No. 3-4, pp. 237-266, 1995

[2] Jevtić, M. B., Gligorić, B., Vukelja D.: Thermal Influence of Dynamic beheviour Turbogenerator Rotor, *Eight World Congress in the Theory Machines and Mechanisms*, IFTOMM, Procedings, Prague, pp. 743/747, 1991

[3] Bently Nevada CO. USA: *Advanced Machinery Dynamics Reference Manual*, SELECTED PUBLICATIONS 1982-1998, Minden, USA, 1998

[4] Milenko, B. Jevtić.: ISTRAŽIVANJE UTICAJA TEMPERATURA U STRUKTURI ROTORA NA DINAMIČKO PONAŠANJE TURBOGENERATORA, *Peta međunarodna konferencija*, Beograd 1996

[5] Jevtić, M.: TERMIČKA NEURAVNOTEŽENOST ROTORA SINHRONIH GENERATORA, *Sedmo stručno savjetovanje o termoelektranama Jugoslavije*, Ohrid, oktobar 1985

[6] Antunović, R.: IMPLEMENTACIJA CDS (KOMPJUTERSKO DIJAGNOSTIČKOG SISTEMA) U TE GACKO, *8 Kongres JISA*, Herceg Novi, jun 2003.

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APPLICATION OF WELDING FOR THE PRODUCTION OF BALLISTIC PROTECTIVE STRUCTURES

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Abstract: *In the common industry and especially in military industry there is a growing need for production of highly effective protective structures. For that purposes the most used materials are armor steels. They belong into a group of the fine-grained, increased strength steels, which are manufactured by intensive thermo-mechanical treatment at high temperatures and later quenching and low-tempering. Combination of the heat and mechanical treatments provides for the fine grains and exceptionally good properties of these steels, while the low-tempering enables relatively high hardness and good ballistic properties. However, sometimes there is a need to weld these steels in order to manufacture some specific assemblies. Since the way these steels are produced this is why the welding can negatively affect the material properties in specific zones of the welded joint, what could lead to worsening of the material's ballistic properties, as well. The aim of this paper was to determine influence of the welding procedure on that mechanical and ballistic properties. In that order the model plates were welded with the specially prescribed technology in three types of the joints: the but-joint, corner joint and the corner joint with the shielding plate. After the welding the test plates were subjected to the ballistic tests which consisted of shooting with three types of live ammunition at different types of the welded joints. At the end the comparative analysis of the results is given.*

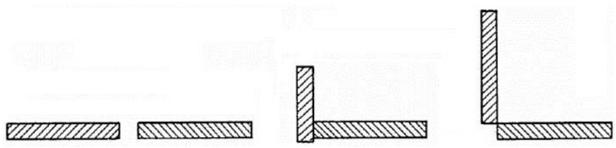
Keywords: *protective structure, welding, armor steels; ballistic properties;*

1. INTRODUCTION

The combat vehicles for the infantry were created from the tendency to increase the efficiency of the tanks and possibilities for their survival on the combat field. The problem that appeared was how to develop the armor, which would guarantee the safety to the personnel by preventing the penetration of the projectile from the anti-armor ammunition into the vehicle, while simultaneously realizing as good as possible its tactical-technical and combat-exploitation characteristics. Taking into account these requirements, it was inevitable to develop the special group of the high-strength steels, known as the armor steels that are being improved [1].
The Swedish company SSAB Oxelösund [2] has the high-strength steels in its production program, where the especially interesting is a group of armor steels, known under the commercial brand ARMOX, which are produced according to the strictly defined manufacturing procedures, [3]. Their excellent properties are resulting from the manufacturing process. They possess a very low content of carbon what positively affects their weldability, while the strength is being achieved by application of the thermo-mechanical processing (TMP) [1, 3]. However, despite their exceptional properties, when the armor is being welded, the worsening of those properties occurs, locally, due to the entered heat. Such spots represent the critical places on the structure and the objective of this paper is to show how those places (various types of the welded joints) behave in the conditions when being hit by the projectiles of different types [4, 5].

2. WELDING OF SAMPLES

The welded joints on combat vehicles, made of this or some other steel, represent the most vulnerable places of the whole structure. The reason for that is the fact that in welding of the armor steels the filler metals must be applied, which produce the weld metal of the significantly lower strength with respect to the base metal. Thus, the appearance of the cold cracks can happen, since the armor steels are very prone to hardening. Besides that, this steel belongs into a group of the conditionally weldable steels, which implies that adequate measures must be taken during the welding. One of the most important measures is to control the heat input, what is explicitly presented by SSAB in specifications of this steel. The heat input is limited to 200 °C, since at the higher temperatures the excessive annealing occurs and thus the loss of all the positive properties induced by the TMP. In this paper are given recommendations that are mandatory to be followed in order to obtain as high quality welded joints as possible. The welding technologies are also proposed, all based on recommendations by the steel manufacturer, as well as the experts that have already dealt with this problem.



a) b) c)

Fig. 1 Schematic presentation of the welded joint: a) butt, b) corner and c) corner-edge

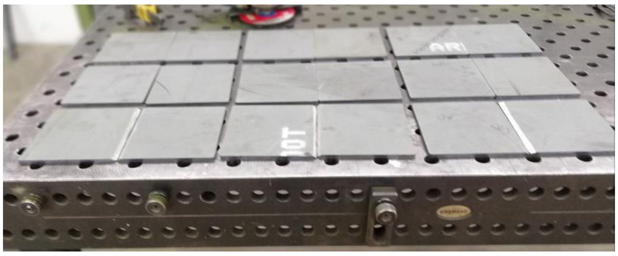
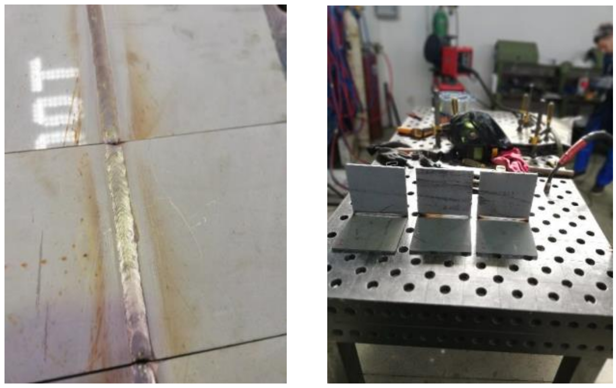


Fig. 2 Plates prepared for welding

Table 1 Used welding parameters

1.	Groove type	V
	Way of preparation	grinding
2.	Wire diameter	1.0 *mm*
	Type	
	Protective gas type	Ar + 2.5
3.	Preheating temperature	125-175°C
	Interpass temperature	150-175°C
	Measurement procedure	Thermo-chalks
	Preheating device	Gas flame
4.	Welding procedure	135 (MMA)
	Welding position	PA
	Welding technology	To the left/75°
	Power	190-210 *A*
	Arc voltage	24.5 *V*
	Current type	DC
	Polarity	+
	Wire feeding rate	6 *m/min*
	Welding rate	21 *cm/min*
	Gas flow	18 *l/min*
	Number of passes	2
	Driving energy	≈ 11000 *J/cm*

The experimental samples, needed for the ballistic tests of the basic zones of the welded joint, were made in the form of the butt, corner and corner-edge joints (Figure 1). The plates' dimensions of the ARMOX 500T steel were200 × 200 × 8.6 mm and they were cut by the laser (Figure 2).
The welding was done using MMA welding procedure. The welding parameters are given in Table 1 while in Figure 3 are shown the plates' appearances after the welding, for all the three cases.



a)

b)

c)

Fig. 3 Welded plates: a) butt, b) corner and c) corner-edge joint.

3. TESTING OF THE WELDED JOINT BASIC ZONES BALLISTIC RESISTANCE

Many countries have prescribed standards regarding the levels of the ballistic protection; the most used by the ARMOX manufacturers are STANAG 4569 (Table 2) prescribed by the NATO and EN 1522, prescribed by the UN, primarily due to the customers' requests [4]. The STANAG 4569 standard refers to degrees of the protection for logistic and light armored vehicles.
The standard includes threats by the ballistic projectiles, of the small and medium caliber, as well as the fragments simulating the penetrators, in order to simulate the artillery actions. It is aimed for the repeatable testing procedures for estimate of the ballistic protection of the armored vehicles' parts and for determination of the critical zones on those vehicles. The threats are divided into five levels, where the first level is related to civilian threats, while the other levels are related for various military threats.

Table 2. Standard STANAG 4569 NATO

Le-vel	Weapon type	Caliber	Dista-nce, *m*	Velocity, *m/s*
I	Rifle	7.62×51-NATO Ball	30	833
		5.56×45-NATO SS109		900
		5.56×45-M193		937
II	Infantry rifle	7.62×39-API BZ	30	695
III	Sniper rifle	7.62×51-AP (WC core)	30	930
		7.62×54R-B32 API		854
IV	Machine gun	14.5×114AP-/B32	200	911
V	Auto-matic cannon	25 mm APDS-TM-791	500	1258

4. RESULTS OF THE BALLISTIC TEST

Though the three samples were made for each type of joints (the butt, corner and corner-edge), the ballistic tests were done at one sample from each group, only. That was done primarily due to the complexity of the experiment and since the obtained data were sufficient to estimate the ballistic resistance. The objective of the experiment was to estimate the degree of damage, namely the type of penetration of the basic zones of the welded joint (the base metal – BM, the heat affected zone – HAZ, the joining zone – JZ and the weld metal – WM) by ammunition of the 7.62 × 39 type: M67 Ball, 7.62 × 51 NATO Ball (Ball M80) and armor bullet 7.62 × 54R B32 API (Dragoon's). The 7.62 × 39 M67 Ball bullet is not prescribed by the NATO standards, but by the Russian standards of the ballistic protection, which is not guaranteed by the SSAB.

The experiment was performed on the test field of the "Prvi Partizan DOO" company in Užice, Serbia, which has decades' long experience in producing the ammunition and the tests of this kind. The finishing, verification and homologation (approval) tests of ammunition are being conducted on this test field. The experiment was executed by the expert staff, according to adequate safety standards. The testing equipment included:

- Test barrel with the cover for measuring the velocity, of caliber 7.62 × 39 mm,
- Test barrel with the cover for measuring the velocity, of caliber 7.62 × 51 mm,
- Test barrel with the cover for measuring the velocity, of caliber 7.62 × 54 mm,
- Stand for the test barrel
- Ammunition 7.62 x 39 M67 Ball, velocity at v25 = 725 m/s,
- Ammunition 7.62 x 51 NATO Ball (Ball M80), velocity at v25 = 830 m/s,
- Ammunition 7.62 x 54R B32 API, velocity at v25 = 790 *m/s*.

The samples of the armor steel, prior to the commencing of the experiment, were firmly positioned in the wooden frames, to prevent the loss of energy due to motion of the plates when hit by the bullet. The distance from the exit hole of the test barrel to the sample was 10 m. According to the experimental plan, the welded joints were positioned in such a way that the weldment was perpendicular to the bullet motion direction, what at the corner and corner-edge joints should present the behavior of the base metal and the heat affected zone at the bullet impact at an angle.

Appearance of the butt joint after the bullet impacts is presented in Figure 4. Total of 10 projectiles were fired of the three calibers [4].

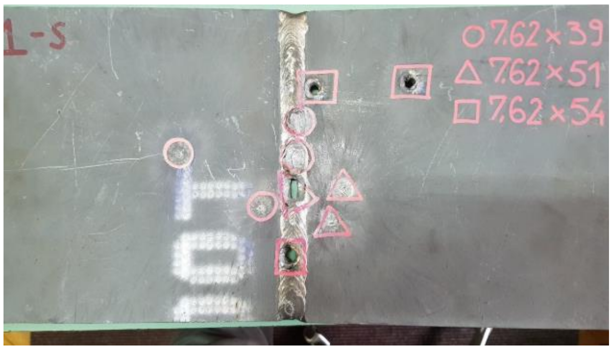


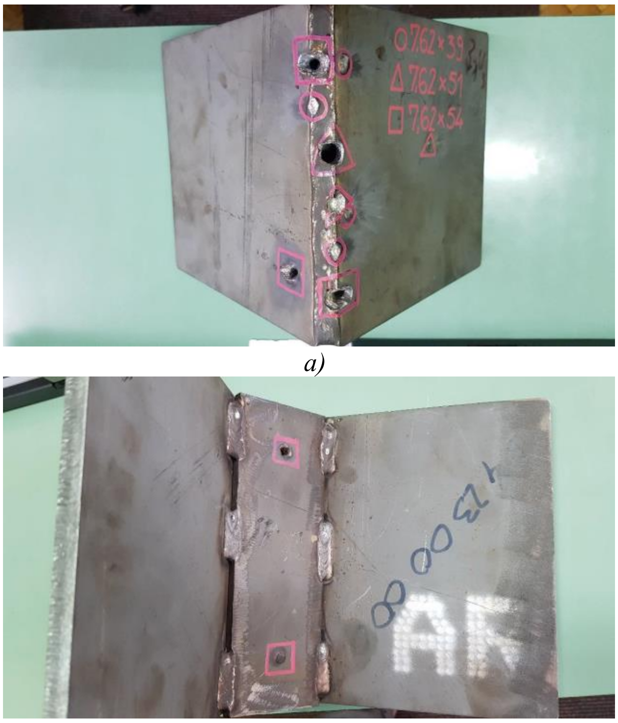
Fig. 4 Appearance of the tested sample of the butt joint from the entrance side

After the tests on the butt joint, the tests of the corner joint were performed, with the samples fixed as described earlier. The total of 9 bullets was fired of the three calibers. The entrance side of the corner joint is presented in Figure 5 [5].

Fig. 5 Appearance of the tested sample of the corner joint from the entrance side.

The penetrated spots – perforations were of the type characteristic for an impact by the sharp pointed projectiles into the armors of the small thickness. In some cases they also appear for the flat bullets' impacts at velocities that are close to the limiting velocities of penetration. Consequences of penetrations of this type are characteristic since the shape of the hole at the exit side resembles the flower petals.

At the end, the corner-edge joint was tested, which on the inside has little platelets made of the same material. The idea is that they should act as a protection in the case that the weld metal and its vicinity have been penetrated. The total of 8 bullets were fired of the three different calibers, into the characteristic zones of the welded joint. Results are presented in Figure 6 [4, 5].



a)

b)

Fig. 6 Appearance of the corner-edge joint with protection: a) at the entrance side, b) at the exit side.

5. CONCLUSION

In this paper the ballistic check the penetration resistance of three types of welded joints' zones were performed. Ammunition used was 7.62 x 39 M67 Ball, 7.62 x 51 NATO Ball, and 7.62 x 54R B32 API. Besides, the whole welding technology of the samples was presented.
Obtained results led to the following conclusions:

- The base metal, the heat affected zone and the weld metal are all bullet proof for the caliber 7.62 × 39. Test by the 7.62 × 51 caliber bullets showed that only the base metal is resistant to penetration.
- For the armor ammunition of the 7.62 × 54R caliber there are no obstacles, i.e. all the zones of the welded joint are threaten, even the protective plates in the corner-edge joint case.

Based on these results, one must recommend that vehicles constructions made of this steel must be so designed that all the zones of the welded joint should be well protected against penetration by any caliber projectiles. The weld metal should be hidden whenever possible, while the butt joints should be strictly avoided in any case. If these recommendations were not followed to the letter, the safety of the personnel in the vehicle, against the projectile penetrating the armour, cannot be guaranteed.
The reason that the welded joint is the weakest place at the structure can be the heat input during welding. amely, the heat generated during welding leads to worsening of the properties of the material in the welded zone (softening of the steel). Although, the steel producer forbid the heating of the steel over 200ºC in order to preserve the good mechanical properties, during the welding that cannot be achieved. Since the welding has to be used for joining that is the reason why we tested different types of joints in order to determine the most favourable option.

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REFERENCES

[1] Arsić, D., Nikolić, R., Lazić, V., Hadzima, B., Aleksandrović, S., Djordjević, M., 2014. Weldability estimates of some high strength steels, *Proceedings of 42. International Conference "Zvaranie 2014"*, Tatranská Lomnica, Slovakia, ISBN 978-80-89296-17-0, pp. 11-21, 2014.
[2] https://www.ssab.com/products/brands/armox, accessed on 12. 04. 2022.
[3] Lazić, V., Arsić, D., Nikolić, R. R., Djordjević, D., Prokić-Cvetković, R., Popović, O., Application of the high strength steel HARDOX 450 for manufacturing of assemblies in the military industry, *Key Engineering Materials*, ISSN 1013-9826, Vol. 755, pp. 96-105, 2017.
[4] Rakičević, M., 2018. Estimation of weldability and selection of optimal welding technology of bulletproof steel ARMOX 500T, MSc thesis, Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia. (In Serbian)
[5] Lazić, V., Arsić, D., Rakičević, M., Aleksandrović, S., Đorđević, M., Marinković, P., Ratković, N., Uticaj vrste zavarenog spoja na balistička svojstva pancirnog čelika ARMOX 500T, Zbornik radova sa 37. Savetovanja proizvodnog mašinstva Srbije, Kragujevac, 2018, 25-26 Oktobar, ISBN 978-86-6335-057-1, pp. 173-177.

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APPLICATION OF NDT TECHNOLOGIES OF TESTED BUTT WELDED JOINTS

Vlatko Trifković

Abstract: *In this research, an experiment was performed based on the comparison of the quality of welded butt joints on three plates, at differently prescribed welding amperage. TIG welding procedure was performed for butt joint welding, after which NDT test technology was applied. The paper performed visual, ultrasonic and radiographic examination, where the difference in the quality control results of the welded butt joint appeared. NDT technology has shown that visual inspection detects surface defects, while ultrasonic and radiographic inspections show volume defects. It was concluded that the occurrence of the error is not a consequence of the change in amperage, but the error of the welder.*

Keywords: *NDT technologies, TIG welding, butt welded joint*

1. INTRODUCTION

The subject of this paper is the testing of butt welded joint, structural steel S235 obtained by TIG welding process. The experimental part of the work was done in the company Termoelektro Oprema d.o.o. in Lopare.

During welding, due to certain omissions in the quality of the basic or additional material or the selection of the prescribed parameters and inappropriate technology, and non-compliance with the same, situations arise in which certain errors in the welded joint are very likely to occur. In order to detect possible defects in time, welded joints are checked by certain tests, which may be with or without destruction. Non-destructive testing is explained here: visual inspection (VT), radiographic inspection (RT) and ultrasonic inspection (UT).

The experiment is based on comparing the quality of welded butt joints on three plates, with differently defined welding currents. The parameter of welding amperage affects the amount of heat, and it affects the quantity and quality of molten material, the dimensions of the weld zone, the structure and mechanical properties of the welded joint [1]. All butt joints are examined visually, radiographically and ultrasound, where a difference in the quality control results of the welded butt joint will appear.

2. NDT TECHNOLOGY

Non-destructive testing is a basic and important tool for quality control of technical materials, production processes, product reliability in operation and system maintenance. It is normally interpreted that non-destructive testing means the use of laws of physics, based on methods for testing materials and products without damaging those materials and products. The decision to accept or reject the results of the examination must be based on:

- thorough knowledge of materials and their properties,
- processes and their effect on properties,
- testing techniques,
- design requirements,
- product applications,
- working conditions, and overall life expectancy

In addition to visual testing, magnetic particle testing or penetrant testing or (with appropriate restrictions) eddy current testing may be used to detect available surface imperfections, and radiographic or ultrasonic testing may be used to detect internal imperfections.

The choice of test methods and levels depends on:

- welding process,
- basic and additional material and processing,
- joint type and geometry,
- component configurations (accessibility, surface condition, ...),
- required level of weld quality,
- of the expected type and orientation of the imperfection.

NDT technology includes: visual control, control by magnets, eddy currents, penetrants, radiography and ultrasound. In this paper, visual, radiographic and ultrasound examinations have been performed, so they will be explained in more detail.

2.1. Visual examination

Visual examination is based on the laws of physical optics, and includes the detection and evaluation of product quality characteristics by the human eye. The eye can detect these characteristics only if there is sufficient contrast of details on the examined surface, which can be achieved:

- differences in brightness,
- the formation of shadows,
- color differences.

In order for a detail, such as a crack, corrosion product, or geometric shape, to be recognizable on a surface, that detail must produce a sufficiently high contrast to the remaining, correct surface. Contrast can occur:

- due to differences in light emission density (reflectivity, shadow casting),
- due to color differences.

The recess (crack, surface pore, groove) on the metal surface "swallows" light more than the rest of the surface, and therefore has less reflectivity than the surrounding surface.

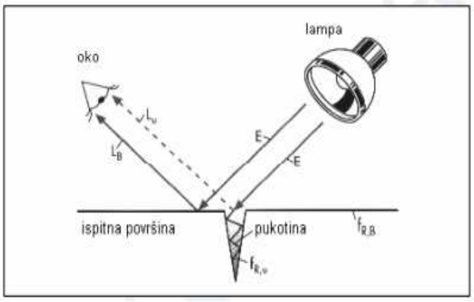


Fig.1. Contrast due to light emission density [2]

Standard BAS EN ISO 17635: 2018, defines the conditions of visual testing and equipment that can be used, requirements to be met by test personnel, visual inspection of repaired welds, and test documentation with information to be provided in the report.

2.2. Radiographic examination (RT)

X-ray and gamma radiation is able to penetrate through matter, and the intensity of that radiation is weak, among other things, depending on the thickness of the irradiated material. Industrial radiography is based on determining differences in the intensity of radiation due to the reduced thickness of the material at the site of discontinuity in relation to the entire, undamaged wall.

Industrial X-ray devices, accelerators or gamma radioactive isotopes Se-75, Ir-192 and Co-60 can be used as radiation sources. Visualization of the distribution of radiation intensity that has passed through the examined object (radiation relief) is performed in standard radiography using industrial X-ray film.

X and gamma radiation differ in location and mode of origin. X-rays are produced by reducing the speed and deflection of accelerated electrons in the electric field of the atom's nucleus (Brakesstralung - braking radiation) and by de-excitation of the excited atom.

Gamma radiation is generated during the energy stabilization of the nucleus of a radioactive isotope after decay by the emission of α or β particles or K capture, emitting γ quanta characteristic of achieving the minimum energy of the nucleus of the newly formed isotope. The source of X radiation in industrial radiography is most often an X-ray tube.

In order to reduce the scattered radiation coming to the film, the film is inserted between metal, most often lead foils. Lead foils, in addition to reducing the intensity of primary radiation, reduce the intensity of scattered radiation to a far greater extent, because it has lower energies than primary.

The secondary effect of lead foils is the transformation of electromagnetic (photoelectric effect, Compton effect) into electronic radiation to which the film emulsion is much more sensitive, so the required blackening of the film is achieved faster. That is why lead foils are said to be accelerating foils. Rays emitted at an angle to the central beam also enter the surface at an angle greater than 0°, travel a longer source-film distance, radiate greater thickness than the central beam, and obliquely project material imperfections onto the film plane [3].

The quality of the prepared radiogram must meet the set requirements.

It is not possible to make a decision on the quality of work on the basis of a poor quality radiogram, for example - a welder. There must be no object in the area of interest on the radiogram. The radiogram must have markings that unambiguously connect it with the location of the object of examination.

Only when the quality of the radiogram satisfies, a radiograph examination may be performed to detect and evaluate indications of imperfection in the subject matter.

2.3. Ultrasound (UT)

Ultrasound examination is based on the physical laws of excitation and propagation of sound. Contact pulse echo technique is most often used (Figure 2).

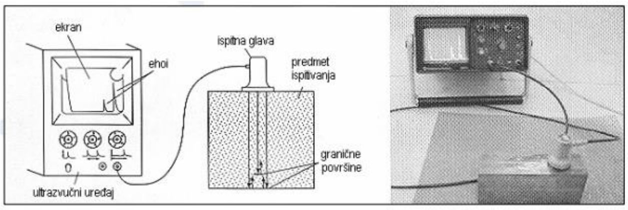


Fig. 2. Scheme of ultrasonic testing device [2]

The ultrasonic device produces high voltage and short duration electrical impulses, which the piezoelectric transducer in the test head converts into mechanical oscillations in the ultrasonic range (f> 16 kHz). These oscillations propagate in the subject matter as sound waves.

Sound waves are reflected on boundary surfaces and the head transducer can receive them. The received sound can be made visible on the screen of the ultrasonic device. With the correct setting of the time base of the device, the length of the sound path to the reflector can be determined, as the distance between the emitted pulse and the received echo, and thus the position of the reflector in the test object. With the correct adjustment of the gain (ie the sensitivity of the device), the reflectivity of the reflector in question can be compared with the reflectivity of a defined artificial reflector (= flat bottom hole, side drilled hole, etc.) and thus its size can be estimated. From the shape of the echo and the echo dynamic curves, one can guess what type of imperfection it is.

Pulsed echo ultrasound technique is used for testing sheets, castings, forgings, pipes, rolled products, welded joints, etc. made of metal, ceramic and plastic materials, mostly thicker than 6 mm. In addition to detecting internal imperfections, ultrasound is also used to measure the thickness of the soundproof wall, and can also be used to characterize materials (speed of sound waves, Jung and shear modulus, etc.), as well as to measure residual stresses. Sound is the mechanical oscillations of particles of matter.

The oscillation of a particle of matter is described by the amplitude (= maximum elongation, i.e. the distance of the particle from the equilibrium position) and the period of oscillation, T, or frequency (f = 1 / T).

The spatial transmission of oscillations is called a wave. During one period of oscillation, the oscillation moves spatially for one oscillatory period, and this path is called the wavelength, λ. The ratio of wavelength and period of oscillation determines the speed of propagation of sound waves:

$$c = \frac{\lambda}{T} \quad \text{ili} \quad c = \lambda \cdot f \tag{1}$$

where: λ - wavelength (mm), c - speed of sound (km / s), f- frequency (MHz).

The speed of sound waves propagation depends on the density of the material and the modulus of elasticity [4].

3. TIG WELDING

TIG welding is a process of electric arc welding in the protection of inert gas with an insoluble electrode where the necessary heat for melting the metal entering the joint (groove sides and additional material) is obtained from the electric arc, which is established and maintained between the insoluble electrode of tungsten or its alloys and the workpiece. When moving the electric arc, the base material melts and additional material is needed as needed. During welding, the tungsten electrode, the molten metal and the area around it are protected from oxidation by inert gas-argon or helium or mixtures thereof. The role of the shielding gas is to protect the electrode and the molten metal which has a pronounced affinity for oxidation in the molten state. Shielding gas is supplied continuously [5]. The TIG process has been perfected and is widely used in the production and assembly of welded metal structures.

It is used for production welding, surfacing and repair welding. It is especially used in welding metals and alloys, which have a high affinity for oxygen (oxidation) in the molten state. These include high-alloy steels alloyed with chromium and molybdenum, aluminum and aluminum alloys, magnesium and magnesium alloys, titanium, zirconium, copper and its alloys, etc. In addition to the mentioned materials, this procedure is practically mostly used in the assembly of various pipelines in boiler building, petrochemical industry, etc., made of low-alloy steels [1, 6]. The TIG procedure is mainly used for performing root welds, while ensuring high quality.

The most influential factor in welding is amperage. By increasing amperage, the melting temperature of the base material increases, and with decreasing amperage, the melting temperature decreases. When increasing the amperage it is necessary to increase the speed of wire addition and welding speed, because the increased temperature melts the base material and creates a weld depression, which manifests itself as a fault. If the flow of gas does not increase with increasing amperage, there is a possibility that impurities will remain in the weld, where the remelted material will not be joined by volume, a cavity or bubble will form, which also manifests as a mistake [7, 8].

Fig. 3. Schematic diagram of TIG welding procedure [2]

4. EXPERIMENT

The experiment was done in the company Termoelektro Oprema, in Lopare. The aim of this paper is to check the quality of a welded joint with a change in current, ie, to compare these three butt joints. Dimensions of the preparation are 300x150 mm, thickness 10 mm, which were cleaned after cutting and whose edges were beveled down at 30 ° as shown in the figure (Figure 4). The technologist wrote a WPS list with a certificate of the material he received from the supplier. Welding specimens, placed at a distance of 3mm, and the welding process itself was performed by a licensed welder based on previously defined WPS (Welding Procedure Specification).

Table 1. WPS 1

Weld	Additional material diameter (mm)	Amperage (A)	Voltage (V)	Gas flow (l / min)
1+n	2	85	10-12	8-9
1	2,4	90	10-12	8-9
1-n	2,4	100	11-13	8-9

Table 2. WPS 2

Weld	Additional material diameter (mm)	Amperage (A)	Voltage (V)	Gas flow (l / min)
1+n	2	110	11-12	18-19
1	2,4	125	11-12	18-19

1-n	2,4	135	12-13	18-19

Table 3. WPS 3

Weld	Additional material diameter (mm)	Amperage (A)	Voltage (V)	Gas flow (l / min)
1+n	2	135	10-12	8-9
1	2,4	160	10-12	8-9
1-n	2,4	190	11-13	8-9

After all three butt joints have been welded, it is necessary to clean the welded joints with a steel brush, and then it is further tested by non-destructive technologies, procedures (VT, RT, UT).

Fig. 4. Preparation of welding positions

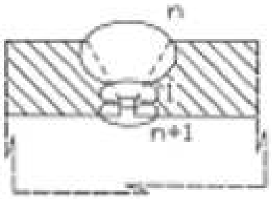


Fig. 5. Welding order

4.1. Test results

Pieces that are welded they are initially visually inspected on both sides, using tools, a hand lamp and a caliper. On the first panel, an inspection was performed from the face of the seam, where the type of error 5012 (BAS EN ISO 6520-2: 2014, undercut short length repeating periodically along the weld seam), ie low weld overhang, in length of 40 mm, size 0.4 mm, which is acceptable for C class. [9] An inspection was performed on the other side of the plate, on the side of the root weld, where error type 4021 occurs (lack of the fusion on the root weld), ie the weld did not pass on the root side of the plate due to low amperage or higher welding speed. at a length of 147 mm, which is not allowed in class C.
Figure 6 shows the radiograph from which it can be seen, error type 401 (lack of fusion), i.e., not remelted base material, but glued weld. Also, error type 517 (bad re-energizing the arc, i.e., surface unevenness at the weld extension site) located on the same side of the root weld. Both errors were rated negatively. Examination of the first plate by ultrasound shows a line indication (glued weld) at a depth of 5-10 mm, periodically, size 0.5 mm, and a maximum length of 4 mm (Figure 7). It also does not satisfy the quality of welds tested by ultrasound.
Visual inspection of the second plate is satisfactory, with no indication of error. Testing of the second plate by radiography, fault type 515 (concavity of the weld) was found, which is acceptable for this class of welded joint (Figure 8). In Figure 9, we can see that the ultrasound image is without findings, i.e. there is no error, where it is assessed that the weld is acceptable. Visual inspection of the second plate is satisfactory, with no indication of error. Examination of the second plate by radiography, error type 515 (concavity of the weld) was found, which is acceptable for this class of welded joint (Figure 8). In Figure 9, we can see that the ultrasound image is without findings, ie there is no error, where the weld is judged acceptable.

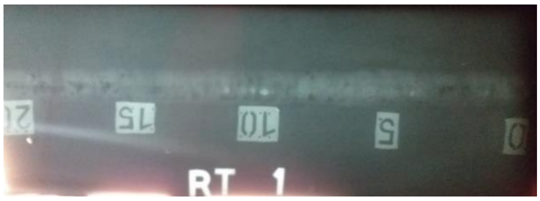


Fig. 6. The first plate examined by radiography

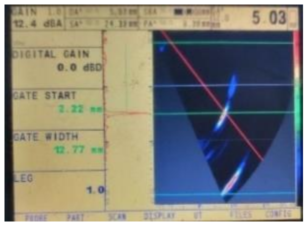


Fig. 7. The first plate examined by ultrasound

Fig. 8. Second plate examined by radiography

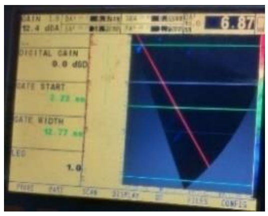


Fig. 9. Second plate examined by ultrasound

Visual examination of the third plate, control was performed on the side of the seam face, where error type 5011 occurs (continuous undercut, ie excessive heat input or retention at the welding site), at a length of 50 mm, at a reference distance of 70-120 mm, and at a reference distance of 205-290 mm, length 85mm, size 1-1.5 mm, which is not allowed in C class. On the same side, error type 509 was found (protek, i.e., there is not enough weld overhang),at a reference distance of 42-43.5 mm, length 1.5 mm and 65-120 mm, length 55 mm, size 1.5 mm, which is not acceptable either. A third fault was found on the same side, fault type 506 (overlap of welds, natek on

the surface of the base material, ie, large cant of welds on the material), at a reference distance of 20.70 mm, length 50 mm, size 2 mm, also not acceptable. On the other side of the plate, ie on the side of the root weld, error type 4021 was found (lack of the fusion of the root weld, ie fast guidance of the welder led to the weld not passing to the other side of the plate), at a reference distance 20-95 mm, length 75 mm, size 1-1.5 mm, also at a reference distance of 130-155 mm, length 25 mm, size 1.2 mm, also at a reference distance 220-240 mm, length 20 mm, size 1 mm, which is not acceptable.
Figure 10 shows a radiographic image, which shows the type of error 401 (lack of fusion connection in the welded joint-on the root side of the weld), ie, the base material is not remelted, which is not acceptable.
Ultrasonic testing of the third plate (Figure 11) is negative, similar to the first plate, but in this case the biggest error is at the bottom of the sheet metal thickness, ie, at a distance of 9.35 mm from the measuring surface. It is a line indication at a depth of 8-10 mm, along its entire length. Welded butt joint on plate 3, not acceptable.

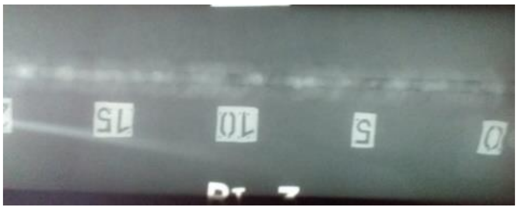


Figure 10. *Third plate examined by radiography*

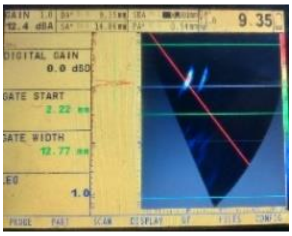


Figure 11. *Third plate examined by ultrasound*

Table 4. Tabulation of results

	Visual	Ultrasound	Radiographic
Sample I	5012,4021	401	401,517
Sample II	/	/	515
Sample III	5011,509, 506,4021	4021	401

From the table it can be clearly concluded that in plates 2, no impermissible errors were observed, while in plates 1 and 3, certain errors occurred. The observed errors are not the result of a change in welding current, but errors in the operation of the welder.

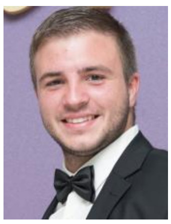
5. CONCLUSION

This paper gives an example of the application of NDT technologies in the testing of butt welded joints, structural steel S235, obtained by TIG welding process. The paper examined three plates, welded with different welding amperage, and concluded that the occurrence of the error is not a consequence of the amperage change, but the error of the welder. This way of testing the technology is common in practice, where we apply it on a high pressure pipe system, gas tanks, ammonia, oxygen.
The disadvantage of ultrasound is testing with sheets smaller than 8 mm, which is not possible to perform and requires greater ability of the examiner, or his experience in testing because the examiner controls the probe. The disadvantage of radiography is expensive equipment and it is harmful to the environment and man.
NDT technology has shown us that visual inspection detects surface defects, while ultrasonic and radiographic inspections show volume defects.
By applying various tests of NDT technology, it was obtained that the plate 2, satisfies the quality of the welded butt joint without error, where in all three tests the welded joint was assessed as satisfactory, while in plate 1 and plate 3 it was not satisfactory.

REFERENCES

[1] Horvat, M., Kondić, V., & Brezovečki, D.: Teorijske i praktične osnove TIG postupka zavarivanja. *Technical journal*, 8(4), 425-432, 2014.
[2] Avdić, S. Predavanja za IWE/IWT. Institut za zavarivanje Tuzla, 2014.
[3] Oruč, M., Sunulahpašić, R.: *Ispitivanje metalnih materijala II – Defektoskopija,* Univerzitet u Zenici Fakultet za metalurgiju i materijale, Zenica, 2012.
[4] Krstelj, V.: *Ultrazvučna kontrola - odabrana poglavlja,* Donena, Zagreb, 953-6313-54-5, 2003.
[5] Dobraš, D., *Zavarivanje*, Univerzitet u Banja Luci, Banja Luka, 978-99938-39-64-4, 2016.
[6] Kralj S., Andrić Š., Osnove zavarivačkih i srodnih postupaka, Zagreb, 1992.
[7] Osmani, H.: Uticaj parametara zavarivanja na kvalitet zavara izvedenih mag zavarivanjem, 4. Naučno-stručni skup sa međunarodnim učešćem “KVALITET”, Fojnica, B&H, 399-406, 2005.
[8] Hasan, A. S., Ali, O. M., Alsaffawi, A. M.: Effect of welding current on weldments properties in MIG and TIG welding. *International Journal of Engineering & Technology*, 7(4.37), 192-197, 2018.
[9] BAS EN ISO 6520-2:2014, Zavarivanje i srodni postupci - Klasifikacija geometrijskih nesavršenosti u metalnim materijalima - Dio 2: Zavarivanje pritiskom.

CORRESPONDENCE



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DRONE FRAME: MATERIALS, CONSTRUCTION AND TECHNOLOGY

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Abstract: *Through development and implementation of technologies like Internet of Things (IoT), Big Data, etc. Unmanned Aerial Vehicles (UAV) or drones have found their application for Industry 4.0. For that purpose, development of drone construction itself to achieve different goals (energy efficiency, greater maneuverability, combination of different equipment for mounting, greater flight time, etc) is constantly advancing. In this paper, construction of drone frame will be discussed through three points of view: used materials, different construction design and applied design and production technologies in modern drone frame design.*

Keywords: *drone frame; drone design; advanced materials*

1. INTRODUCTION

Industry 4.0 is a new stage in the organization and control of industrial value chain, based on cyber-physical systems. It represents the current trend of automation and data exchange in manufacturing technologies, that include cyber-physical systems, IoT (Internet of Things), cloud computing and cognitive computing. Cyber-physical systems create capabilities that are needed for smart factories (like remote monitoring, etc.) [1]
The purpose of automation and cyber-physical systems is to eventually replace certain segments of human labour. Drones, or UAV-s (Unmanned Aerial Vehicles) are considered as the next breakthrough in Industry 4.0. Autonomous drones have had huge impact on industrial businesses function. Internet of Things, Big Data and drones are all technologies that will inevitably overlap. Figure 1. shows the technology that represents pillars of Industry 4.0. [2]
Various specific features and technological measures, regarding Industry 4.0, in drone practices are: [2]

- Rise of Artificial Intelligence for Accurate Operations
- Sensors for Electric and Magnetic Field Strength
- Drone for Cell Phone Signals and Humidity
- Sensors for Atmospheric Pressure
- Sensors for Temperature
- Utility of IoT and other Digital Practices
- Throughout IoT Aspects
- Data Acquisition or SCADA

Fig.1. Pillars of Industry 4.0 [2]

The connection of drones to IoT is through possibility of drone wireless network connecting to control system. Drone can send monitoring data of temperature, humidity, air pressure, etc. It can also be used as an extension of stationary sensor network to monitor the places where sensors can not be placed.
Various dimensions of drone application for Industry 4.0 can be seen on Fig. 2.
The main segments are see, sense, move and transform [2]. Through these segments can be observed the versatility of drones' capabilities and its usage possibilities in Industry 4.0.

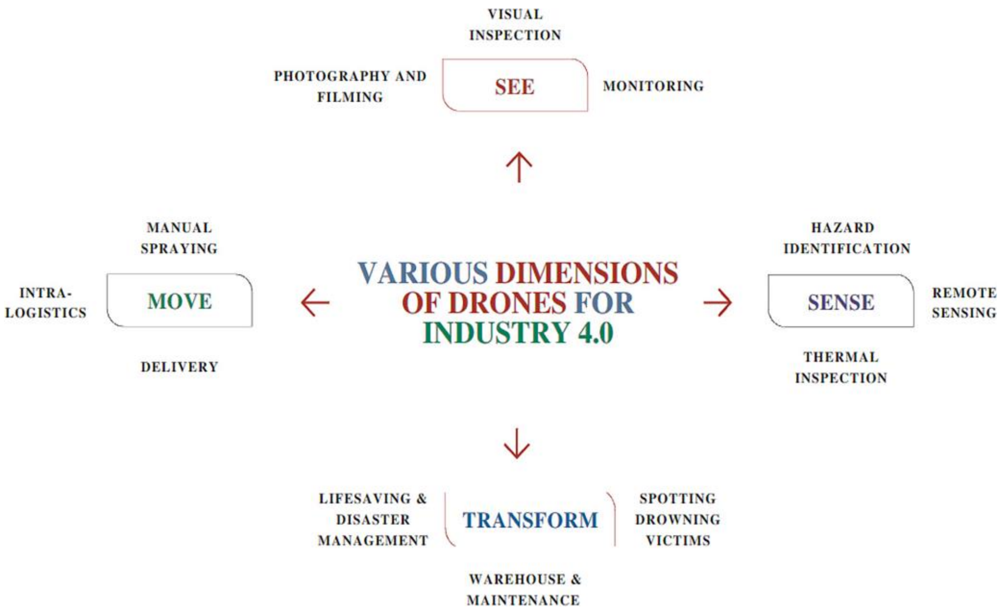

Fig.2. Illustration of various dimensions of drones for Industry 4.0 [2]

Power consumptions of drones is determined through consumption electronic elements and drone weight. The greater the weight of drone the higher is power consumption. Also, the number of mounted sensors is weight dependent.

In that context, the design of drone frame, besides the needed structural support, tends to reduce the overall drone weight.

Frame design depends on drone application, its capabilities, maneuverability, or basic economy (cheaper materials or cheap replaceable frame parts).

2. DRONE

2.1. Types and frame design

Construction, used materials and application of drone depends of drone type.

There are several methods for drone classification. One of them is by physical type: [3]

- Multi-rotor (or multirotor) drones
- Fixed-Wing drones
- Single-Rotor Helicopter drones
- Fixed-Wing Hybrid VTOL

Multirotor drones are most used today for industrial purpose, because of their ability to hover. They have VTOL (vertical takeoff and landing) capabilities. Multirotor drones, as name suggesting, have multiple rotors in order to fly (usually three, four, six or eight). Their usage is limited because of short flight time, and they are not used in large scale surveying. Figure 3 shows example of industrial grade octorotor drone.

Fixed-Wing drones are used for large scale surveying. Their flight time can be several hours, and can achieve greater flight distance. The design of Fixed-Wing drone is one long wing used for flight (Figure 4). The obstacle in usage is that they need a runway for takeoff (or some sort of catapult system for takeoff) and landing.

Fig.3. Industrial drone Skycrane [4]

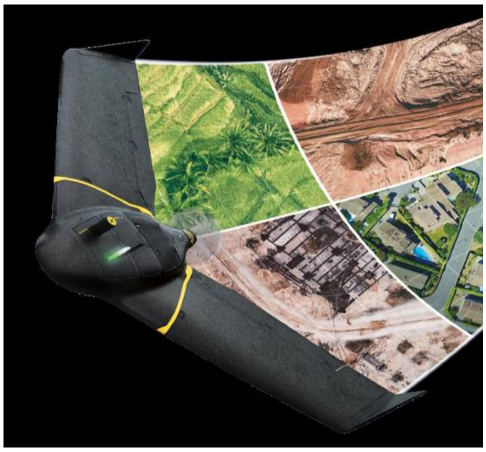

Fig.4. SenseFly eBee X fixed-wing drone [5]

Single-Rotor Helicopter drones are also VTOL UAV-s. They fly with one rotor, and have capabilities between fixed-wing and multi-rotor drones (greater flight time and can carry heavier payload). Depending on size, they use gas or electric energy as fuel. Figure 5. shows Airboxer Single-Rotor Helicopter drone.

Fixed-Wing Hybrid VTOL (example on Figure 6) combines the long flight time of Fixed-Wing drones and capability of vertical takeoff and landing. Thus, discarding the need of long runway in order to be airborne.

Fig.5. Industrial drone Airboxer [6]

Fig.6. Carbonix Volanti: fixed wing carbon composite industrial drone with multirotor VTOL capability [7]

What drone to use depends on the defined role (inspection, survey,…). Also, the frame construction and accessories, can depend on same thing. For example, on Figure 7 is Flyability Elios 2 drone, that is used for indoor inspection. Problem with that task is that there are a lot of obstacles and tight spaces. So, in order to protect the drone from physical damage, the design solution presented on Figure 7. is cage around the drone.

Fig.7. Flyability Elios 2 [8]

On frame design the great impact had the development of CAD/CAM/CAE software and computer optimization.
Frames can now be examined through computer simulations and optimized without need for manufacturing prototypes. With the development of 3D printing, the optimization of internal drone frame structure is also made possible.
There are several optimizing methods used in drone frame optimization like: structural optimization [9] through analysis of different frame configurations; generative design [10,11] method based on topological optimization; optimization of lattice structures [12-14], etc. These optimization methods are used for reduction of drone weight without loosing any mechanical properties (without compromising the frame integrity and functionality). Example of optimized design is shown on Figure 8.

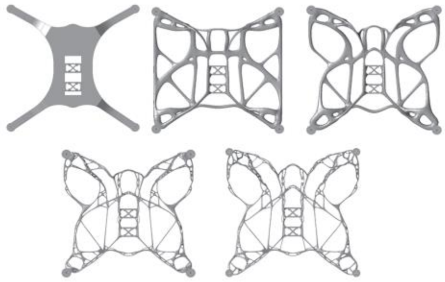

Fig.8. Different iterations of generative design optimization process [11]

2.2. Materials

There are wide range of materials used for construction of drone frame:

- wood
- metal
- PCB
- fiberglass
- plastic
- composite materials
- biodegradable and recycled materials

Drone frames made of wood are cheap solution for building. The thinking behind wood frames is that is cheaper to replace frame part then invest in stronger materials. Frames are usually made from lightweight wood or from plywood elements (Figure 9).
Metals that are used in manufacturing drone frame are usually aluminium, titanium or various alloys. Example of alloy is AZ91D used in Mavic Air frame that consists of 90% magnesium, 9% aluminium and 1% zink [15].
Metals used for drone frame need to be lightweight and strong. Other criteria is manufacturing (how easy is to manufacture it and what is the price of manufacturing).
Plastic is now one of the most used material, especially with the expansion of 3D printing technologies.

Fig.9. Plywood drone frame [16]

Fig.10. Metal drone frame [16]

PCB drone frame represents the integration of electronic and frame design. The PCB frame allows the mounting and wiring of electronic components on itself (Figure 11), thus reducing the number of additional necessary electronic modules (thereby reducing drone weight)

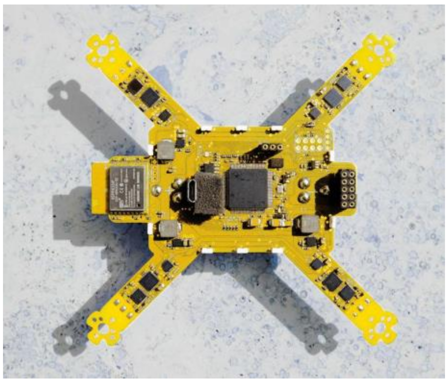

Fig.11. PCB frame with electronic components [16]

For drone frame G10 fiberglass material (micarta or garolite) is usually used as a cheaper solution to carbon fiber material. It is very stable over temperature and absorbs low amount of moisture. It has good strength to weight ratio. Of course, drone frame can be made from pure fiberglass and epoxy resin. Figure 12. shows tricopter with frame made from fiberglass.
Plastic material are now used widely, because of commercialization and availability of 3D printers (especially FDM printers). There is wide variety of thermoplastic materials used [17]:

- ABS (high strength, high ductility, great machinability and thermal stability)
- PLA (high strength, medium durability, low flexibility, biodegredable)
- Nylon (lightweight, tough, good impact and temperature resistance, high fatigue resistance)
- PETG (more flexible and durable than PLA and easier to print than ABS)
- TPU (strong, wear-resistant, elastic substance that absorb vibration, good for harsh environments)

On Figure 13. is shown the drone frame made from plastic via 3D printing.

Fig.12. Tricopter made from fiberglass frame [16]

Fig.13. 3D printed parts of drone frame [16]

The composite material used in used for manufacturing drones are usually fiber composite polymer (or carbon fiber) with foam (based on polymath-acrylimide) [18]. The great characteristic of carbon fiber composite is excellent strength to weight ratio. Because of that, the carbon fiber replace metal in construction of frames, or use in construction with metal parts. On Figure 14, the LA100 drone is shown that is build using aluminium and carbon fiber composite material and foam. The combination provides lightweight but sturdy structure.
Biodegradable and recycled materials - one of the solutions for drone frame materials is based on environmental protection and sustainable development. Perdana et al. [19] examined mechanical properties of composite waste material based on styrofoam, baggase and eggshell powder and conclude that that type of material can be used in drone frame manufacturing.
Breznik Natural Fiber Composites construct a drone frame made from natural fiber and PLA material that can biodegrade in two weeks after being buried (Figure 15). [20]

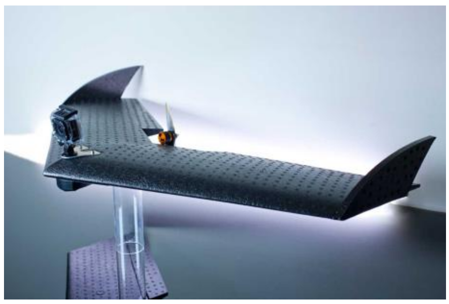

Fig.14. LA100 drone [21]

Fig.15. Drone frame made from biodegradable materials [19]

Because of the some harsh environmental condition that drones can be put (large temperature range, corrosive environment etc.) for industrial usage, materials and their usage for drone manufacturing are constantly developing.
Graphene (for use in reinforcing carbon fibre composites), basalt fibre reinforced composites, ceramic-matrix composits are used for improvement of high temperature resistance, greater resistance to deformation and abrasion.[22]
Myeong W.C. et al. [23] designed fire proof dron using and aramid fiber armor and air buffet layer that can be used in fire accidents monitoring in urban areas.

2.3. Manufacturing technologies

Manufacturing technologies used in drone frame production depends on material used. The development of Additive Manufacturing enabled the creation of complex objects. The design and manufacturing process of UAV using conventional fabrication method and Additive manufacturing techniques is shown on Figure 16.

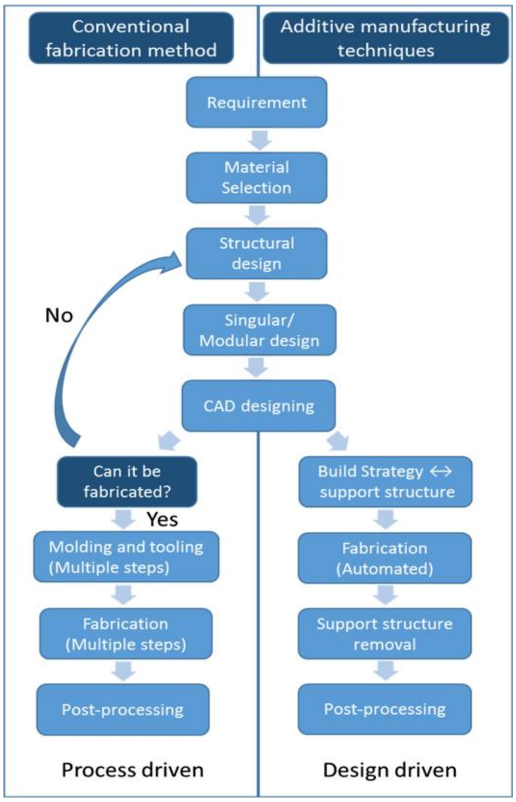

Fig.16. PCB frame with electronic components [24]

3. CONCLUSION

UAV or drone is a versatile tool that can have multiple roles today. As a industrial tool, it can help to monitor processes, to do a maintenance of systems, do deliver packages and much more. That is important especially for the conditions where humans can not go or where is dangerous for them.
Drone frame represents the backbone of drone. The right selection of type, used material and available technologies can provide the balance between the required characteristic and price. In exploitation, the most important element is, besides the quality fulfillment of required application, the weight in order to achieve the longer flight time, and thus lower expences.

REFERENCES

[1] https://www.i-scoop.eu/industry-4-0/#:~:text=Industry%204.0%20has%20been%20defined,and%20creating%20the%20smart%20factory%E2%80%9D. - Industry 4.0 and the fourth industrial revolution explained, Accesed on: 2022-04-20

[2] Javaid, M., Khan, I.H., Singh, R.P., Rab, S., Suman, R.: Exploring contributions of drones towards Industry 4.0. *Industrial Robot: the international journal of robotics research and application.* Vol. 49, No. 3, pp. 476-490, ISSN 0143-991x, 2022.

[3] https://www.dronethusiast.com/types-of-drones/#:~:text=There%20are%20four%20main%20physical,and%20duration%20of%20the%20flight. – Types of Drones: Explore the Different Types of Professional Drones, Accesed on: 2022-04-21

[4] https://www.aeroexpo.online/prod/multirotor-service-dronede-gmbh/product-173931-3998.html - Industrial drone Skycrane, Accesed on: 2022-04-21

[5] https://www.sensefly.com/drone/ebee-x-fixed-wing-drone/ - SenseFly eBee X brochure, Accesed on: 2022-04-21

[6] https://www.aeroexpo.online/prod/high-eye-bv/product-181362-19158.html - Industrial drone Airboxer, Accesed on: 2022-04-21

[7] https://newatlas.com/carbonix-volanti-vtol-fixed-wing-industrial-uav/48253/ - Loz Blain – Hybrid VTOL fixed-wing drone flies for 2+ hours, Accesed on: 2022-04-21

[8] https://www.flyability.com/elios-2- ELIOS 2 intuitive indoor inspection, Accesed on: 2022-04-20

[9] Aswin Kumar, V., Sivaguru, M., Rohini Janaki, B., Sumanth Eswar, K. S., Kiran, P., Vijayanandh, R., Structural Optimization of Frame of the Multi-Rotor Unmanned Aerial Vehicle through Computational Structural Analysis, *Journal of Physics: Conference Series 1849, 012004,* 2021, doi:10.1088/1742-6596/1849/1/012004

[10] Bright, J., Suryaprakash, R., Akash, S., Giridharan, A.: Optimization of quadcopter frame using generative design and comparison with DJI F450 drone frame, *IOP Conf. Series: Materials Science and Engineering 1012, 012019,* 2021. doi:10.1088/1757-899X/1012/1/012019

[11] Prinsloo, J.V., Minnaar, N.J., Vermeulen, M.: design of a “large” unmanned aerial vehicle frame for metal additive manufacturing on the aeroswift machine, *In Proceedings of 19th Annual Conference Additive Manufacturing as a key driver of the 4th industrial revolution,*141-153, Johanesburg, ISBN: 978-0-620-80987-0, 2018.
[12] Pan, C., Han, J., Lu, J.: Design and Optimization of Lattice Structures: A Review. *Applied Sciences.* Vol. 10, pp. 1-36, 2020.
[13] Maconachie, T., Leary, M., Lozanovski, B., Zhang, X., Qian, M., Faruque, O., Brandt, M.: SLM lattice structures: Properties, performance, applications and challenges. *Materials and Design,* Vol. 183, 108137, 2019. https://doi.org/10.1016/j.matdes.2019.108137
[14] Patel, S., Bhoi, A., Maurya, V., Wankhede, A., Bakshi, R.: Design and test 3D printed lattice structure for UAV. *International Research Journal of Engineering and Technology (IRJET).* Vol. 07, No. 05. pp. 7169- 7174, ISSN: 2395-0056, 2020.
[15] https://www.letusdrone.com/what-are-consumer-drones-made-of/ - Hall, T., What are Consumer Drones Made of? Accesed on: 2022-04-19
[16] https://drones.stackexchange.com/questions/877/what-is-a-good-alternative-to-carbon-fibre-for-a-quadcopter-frame - Drones and Model Aircraft, What is a good alternative to carbon fibre for a quadcopter frame?, Accesed on: 2022-04-20
[17] https://facfox.com/docs/kb/best-materials-for-3d-printed-drone-parts - Best materials for 3D printing drone parts. Accesed on: 2022-04-19
[18] ElFaham, M. M., Mostafa, A. M., Nasr, G. M.: Unmanned aerial vehicle (UAV) manufacturing materials: Synthesis, spectroscopic characterization and dynamic mechanical analysis (DMA). *Journal of Molecular Structure*, 127211. 2017. doi:10.1016/j.molstruc.2019.127211
[19] Perdana, M., Prastiawan, Hadi, S.: Mechanical Properties of Composite Waste Material Based Styrofoam, Baggase and Eggshell Powder for Application of Drone Frames, *IOP Conf. Series: Earth and Environmental Science 97, 012034,* 2017, doi :10.1088/1755-1315/97/1/012034
[20] https://www.hackster.io/news/breznik-s-biodegradable-drone-frame-is-an-eco-friendly-way-to-build-your-own-quadcopter-53537ee397dc - Halfacree, G., Breznik's Biodegradable Drone Frame Is an Eco-Friendly Way to Build Your Own Quadcopter, Accesed on: 2022-04-20
[21] https://www.smashingrobotics.com/overview-fixed-wing-camera-drones-lehmann-aviation/ - Dan Mihai, Overview of Fixed Wing Camera Drones from Lehmann Aviation. Accesed on: 2022-04-19
[22] https://valourconsultancy.com/drones-material-business/ - Drones – are these material to the business. Accesed on: 2022-04-19
[23] Myeong W.C., Jung, K.Y., Myung, H.: Development of FAROS (fire-proof drone) using an aramid fiber armor and air buffer layer. *In proceedings of 14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI).* 204-207, ISBN: 978-1-5090-3056-9. 2017. DOI: 10.1109/URAI.2017.7992713
[24] Goha, G.D., Agarwalaa, S., Goha, G.L., Dikshitb, V., Singa, S.L., Yeonga, W.Y.: Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential. *Aerospace Science and Technology*. Vol. 63, pp. 140-151, ISSN: 1270-9638, 2016. http://dx.doi.org/10.1016/j.ast.2016.12.019

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CUSTOM DESIGN OF AN ORTHOPEDIC HAND CAST USING VIRTUAL SIMULATION, 3D PRINTING AND EXPERIMENTAL VERIFICATION

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Abstract: *This paper presents the design process of an orthopedic hand cast. The main goal was doing research in the field of already existing medical hand casts and innovative 3D printed hand casts, as well as creating a new orthopedic hand cast design which incorporates the Voronoi structure as a topology optimization technique. The additive manufacturing process of 3D printing is chosen due to its ability to create custom products which fit the needs of any specific user, as well as the complexity of the design, the pattern and the build-in mechanism. The design process includes taking custom measurements of a specific user, 3D modelling an orthopedic hand cast and simulation testing to verify said cast.*

Keywords: *orthopedic hand cast, 3d printing, ergonomics, virtual simulation*

1. INTRODUCTION

Orthopedic casts are devices used to protect and support broken or injured joints or bones. They stabilize and hold anatomical structures in place until healing is confirmed [1]. The usual orthopedic cast is made of everyday materials such as plaster or fiberglass, which is later easily molded to the shape of the injured body part.
Considering the additive technology of 3D printing is rapidly growing and expanding its uses, its use in medicine is inevitable [2]. This research is focused on the process of an engineering design in order to develop a 3D printed orthopedic hand cast.
By using the advantages of 3D printing, we can create strong and affective orthopedic hand casts, custom made according to the user's hand dimensions and injury location [3-4]. Considering the model would need to be modelled in a 3D software, we can implement interesting designs and increase the likeability and uniqueness of the hand cast.
One interesting, yet useful way of improving an orthopedic hand cast design is by using the topology optimization technique Voronoi. We can implement the Voronoi pattern in order to reduce the material required for manufacturing and overall cost [5], as well as improve air circulation, which is of vital importance in such product. Additionally, thanks to the unique and interesting nature of the Voronoi pattern itself, we increase the esthetic design of the hand cast, and contribute to the user's comfort. In the case of regular plaster casts, the user is uncomfortable, itchy and cannot do everyday activities freely – such as showering, because the cast cannot get wet. With a 3D printed hand cast, and the use of Voronoi, the user can easily reach itchy spots, as well as use the cast in the shower, due to the material used.
In summary, we can use the power and adaptability which 3D printing provides, in order to create innovative and useful products.

2. LITERATURE REVIEW AND MARKET RESEARCH

An important step in the design process is doing market research. In order to determine the opportunities, strengths and problems which we might face, already existing 3D printed orthopedic hand casts have to be examined. With this analysis we can examine and evaluate possible faults, and find solutions to the problems which we might face.
A 3D printed orthopedic hand cast is a fairly new product on the market, with few to none commercially available products [6-7]. The field is continually being worked on, and the products are still vigorously tested. Despite all the advantages these casts have over regular plaster orthopedic casts [8], they are rarely used as a replacement.
Among the first 3D printed orthopedic hand casts is the CORTEX cast (Fig. 1.), developed in 2013 by Jake and Ollie Evill [9]. What is unique about this cast is the implementation and use of x-ray and the 3D scanning technology. Thanks to the use of this combination of technology, the orthopedic cast is made not only according to the arms parameters, but according to the location of the injury as well.

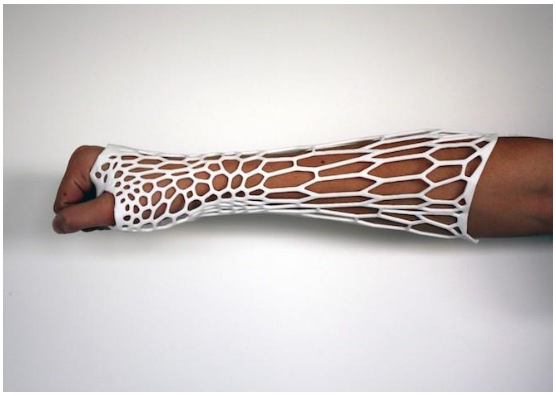

Fig.1. The CORTEX 3D printed orthopedic hand cast [9]

The cast is made of 2 parts, which are connected with a snap fit (Fig. 2.). In the area where the hand should be places, we notice drastic condensing of the Voronoi mesh, which assists and adds to the comfort in the wrist area. This orthopedic hand cast is not commercially available yet, as it is being worked on towards its improvement.

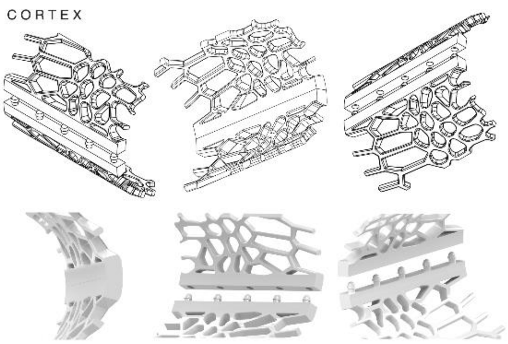

Fig.2. The snap fit connections used in the CORTEX cast [9]

The Osteoid medical cast (Fig. 2.) was designed by Deniz Karasahin in 2014 as part of the A'Design Award & Competition. Deniz won the gold award-winning design for his cast [10].

Fig.3 The Osteoid 3D printed hand cast [10]

The idea of this cast, apart from fixing the arm in place, is to ensure and promote fast bone recovery. That recovery of the bone is done by the LIPUS technology. A signal is being transported through the tissue to the bone, where cells transformed this signal into a mechanical biochemical response, through mechano-receptors. This way, production of cyclo-oxygenes 2 (COX-2) is enhanced, which stimulates fracture repairing molecules to enhance [11].
In terms of design, the cast is made out of 2 parts which can be fixed together like a jigsaw puzzle. A central hole passes through the edges of those pieces. Inside, a flexible pin (Fig.3.) can be inserted in order to tightly secure the two pieces together. This type of a connection is invisible, and hidden inside the cast, which makes the cast easy to wear under clothes.

Fig.3. The flexible pin which passes through the central hole in the Osteoid hand cast [10]

ActivArmor (Fig.4.) is the only company in the USA which designs and produces commercially available 3D printed orthopedic hand casts. This company offers hand casts for everyone, whether the cast be fixed of removable according to the injury of the user. Unlike the previously mentioned 3D printed orthopedic hand casts, ActivArmor offers orthopedic hand casts for arms and legs, in different shapes and sized, made and designed according to the location of the injury. The time required for the design and production of these orthopedic casts is 2 days [12].

Fig.4. ActivArmor's 3D printed various hand casts [12]

This orthopedic hand cast consists of two, “clamshell-like” halves, which are then fitted onto the patient’s affected body part. It can be locked on like a cast or removed like a splint to allow swelling of an injured area to subside. When locking the two parts, an elastic drawstring is used.
In conclusion, the 3D printed orthopedic hand cast is new to the market, but very popular, considering its advantages over regular plaster casts. The field is being worked on, and various interesting designs can be made. After looking into the existing cast designs, we can conclude that we need to design a connection for a multiple part cast and look into the Voronoi mesh, its condensing or loosening, in order to achieve the best results.

3. ERGONOMIC REQUIREMENTS

When designing a product which comes in contact with the user by touch, feel, comfort, we have to take a look into the required ergonomics. This specific product is not only held and felt, but it is used to aid and help in a case of injury and wound. Because of the fragile situation the user is in, we have to be specific and careful when designing said product.
In order to specify the product as fine as we can, it is needed to measure specific, pre-defined areas and parts of the hand, with which measurements we can create a custom, comfortable, aiding orthopedic hand cast in a 3D environment. A different, yet reliable approach, would be to 3D scan the hand of the user in order to further develop the orthopedic hand cast in a 3D model [13].
This paper presents the design process of creating a custom orthopedic hand cast which includes taking precise hand measurements and further transforming them into a 3D model with the appropriate specifications.
The measurements which were taken are separated into 3 parts: the maximum width and maximum length of a specific circumference, located at a specific height.

4. DESIGNING THE ORTHOPEDIC HAND CAST AND 3D MODELLING

After considering all the aspects, a new orthopedic hand cast design was proposed. The process consisted of transforming the previously taken measurements into a 3D model in a modeling software. We divided the design process into three stages (Fig.5.): modeling the base form of the hand according to the previously taken measurements, creating a cast design over the 3D model of the user’s hand and finalizing the 3D model of the cast by adding all the required functional elements.
During the first stage of the design process, attention and light is shone on the basic shape and form by using overall dimensions of the user’s hand and the measurements previously taken. The hand resembles a loft 3D model.
In the second stage of the design process, the orthopedic hand cast 3D model is started to come alive. Over the 3D model of the user’s hand, a cast is modelled. Of course, the comfort, tightness and breathability is taken into consideration. This action ensures fulfilling the required ergonomic needs as well as acquiring assistance and aid in the injured part of the hand.
In the final stage of the design process, the model was finalized by adding the functional assets – the connections, which would connect the 2 parts of the hand cast. In this final stage the Voronoi mesh was added to the model as well.

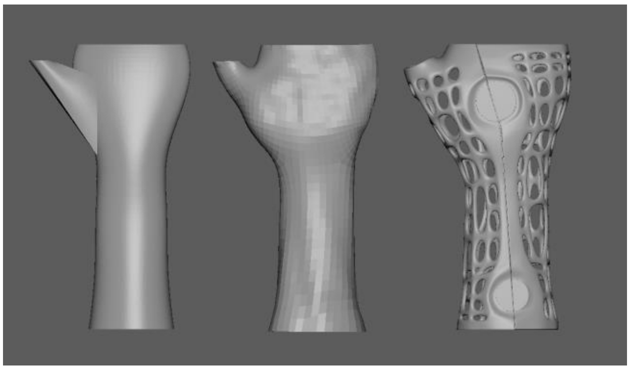

Fig.5. The 3 stages of the cast’s 3D modelling

The division into a 2-part model is of high importance considering the user is injured and cannot fully move the hand or wrist. This way we are ensured the user comes in full contact with the hand cast comfortably, without need of additional hand movement. However, this division increases the complexity of the design and introduces a new asset which needed to be designed – the connections.
In order to ensure total comfort and complete coverage of the user’s hand, two ball joint connections were added to the back of the hand cast (Fig.6.). The ball joint connections ensure easy opening and closing of the orthopedic hand cast. Using two ball joints, positioned in two different locations, the manufacturing process is simplified. This way, we can 3D print the entire orthopedic hand cast in one part, which saves us preparation and manufacturing time.

Fig.6. The back side of the cast, featuring the 2 ball joints

After securing the back side of the hand cast, it was needed to ensure the stability and strength of the front side of the hand cast. On the front side of the cast, two circular elements were introduced, one half of the circle positioned on one part of the cast, the other half of the circle positioned on the second part of the cast. To fulfill the purpose of stability, regular elastic bands can be wrapped around the circular elements, temporarily locking them, securing them and the entire cast altogether. Additionally, because of the use of everyday items such as simple elastic bands, we are ensured countless times of opening and closing the cast.

Fig.7. The front side of the cast, featuring the 2 circular elements

A final additional aspect which needed to be designed and taken into consideration was air circulation. In order to achieve maximum air circulation, various openings in the 3D model were put. Besides improving air circulation, the openings contribute towards easier manufacturing, as well as reducing the required material needed for manufacturing. The best way to achieve various openings, whilst maintaining the needed strength and stability, was by using the Voronoi mesh pattern.

The Voronoi mesh pattern was applied to the entire 3D model, with some needed exceptions. The mesh was excluded along the edges of the entire 3D model in order to preserve the acquired strength and stability. Additionally, other areas had to stay preserved, such as the area around the thumb, and between the thumb and palm.

5. VIRTUAL TESTING

Implementation of virtually testing the orthopedic hand cast is of crucial meaning. By virtually testing the cast, we can examine its performance and asses the quality. Said virtual testing was done using the Solidworks Simulation software package. The aspects which had to be checked and examined included stress and displacement.

When setting up the virtual testing, some boundaries and conditions have to be applied. For this specific test, we wanted to examine how much stress and displacement the orthopedic hand cast can endure if the hand was to suddenly collide into a foreign object (wall, table, etc).

Considering the product was to be manufactured using 3D printing, the material used in the virtual testing is PLA (poly-lactic acid), a polymer used in 3D printing. PLA has a yield strength of 60 MPa.

Considering accurate information and results are always wanted, some parameters were previously defined. For the need of the simulation, the orthopedic hand cast 3D model was fixed in the bottom portion. Fixed fixtures were assigned to the back surface along the edges of the back side (shown in Fig.8. with green arrows).

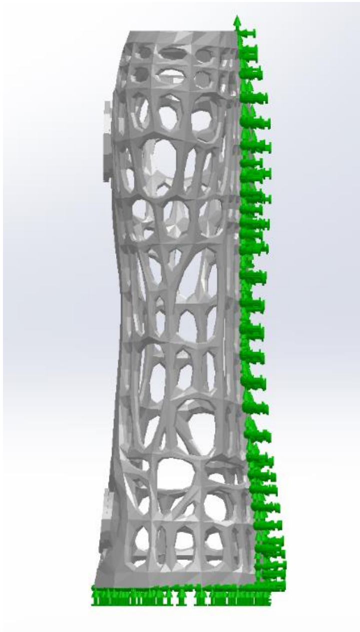

Fig.8. (Green) fixture symbols, showing degrees of freedom along the edges of the cast

The external load and force which was used for the test was a specific force located in the frontal part of the cast. The force was virtually placed on the circular elements on the front side of the hand cast (shown in Fig.9. with purple arrows). For this analysis, the force which this orthopedic hand cast is subjected to is 200 [N].

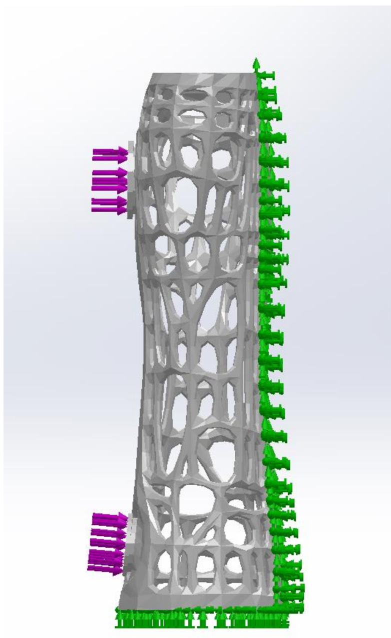

Fig.9. (Purple) external loads and forces symbols which subject the cast

In order to receive precise information, we had to divide the model into a mesh with a finite number of elements. In our case, the orthopedic hand cast model has a fairly complex shape, which means it has to be divided into as many small finite elements as possible, a very fine mesh. When the finite number of elements were created, the mesh consisted of 135160 finite elements and 240434 nodes. The size of each element is 2.85mm.

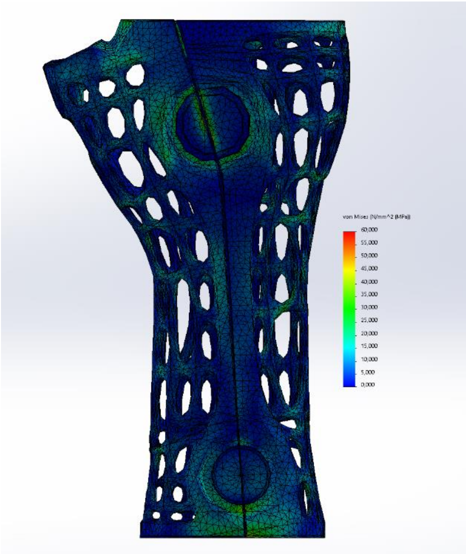

Fig.10. The stress (von Mises) values found in the bottle while under the previously specified external loads

The maximum stress value (Fig.10.) obtained under the external load is 60 MPa, while the maximum displacement (Fig.11.) is 3.204mm. The maximum displacement occurs in the top portion of the orthopedic hand cast.

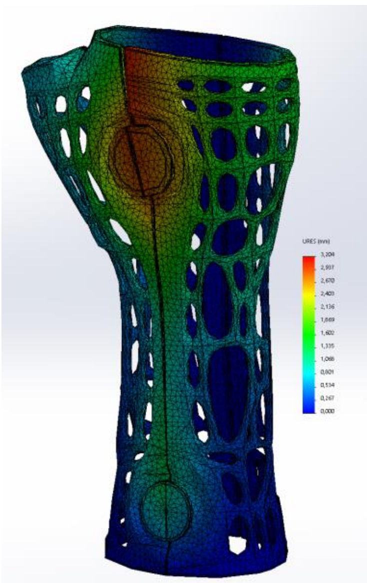

Fig.11. Displacement values found in the cast while under external loads

From this analysis we can conclude that the orthopedic hand cast is strong and reliable to aid the injured, even when under bigger load.

6. PROTOTYPE VALIDATION

A further note into the orthopedic hand cast's validation was performed. For that cause, the orthopedic hand cast was 3D printed, and later tested on the user whose measurements were previously taken and used to create the said hand cast.

Fig.12. Putting the prototype of the cast on

The process of putting the orthopedic hand cast on, without causing pain and discomfort to the user is as shown in Fig.12 and Fig.13. Firstly, the cast is opened, then the thumb is inserted in its opening. Secondly, by rotating half of the cast around the ball joints, the hand cast is closed around the rest of the hand, surrounding the wrist, hugging it perfectly. In order to even further secure the hand cast, small elastic bands were wrapped around the circular elements in the front of the cast.

Fig.13. The finished prototype on the user's hand, locked using elastic bands wrapped around the circular elements

7. CONCLUSION

The main objective of this paper was to design an orthopedic hand cast using 3d modelling software, virtual testing and prototype validation.
The new proposed design implements the use of the Voronoi pattern for topology optimization, air circulation and increased comfort, as well as to give an appealing and interesting overall look. The orthopedic hand cast design is a two-part hand cast, connected with ball joints which are easy to 3D print, yet can endure the needed actions – everyday opening and closing of the hand cast.
Considering the orthopedic hand cast would be custom made according to the user's hand measurements, the ergonomics are at a maximum level.
Virtual testing was confirmed by using the software package SolidWorks Simulation, simulating processes with finite element analysis. To even further validate the design, a 3D printed prototype was made. The custom made orthopedic hand cast fits the user perfectly, with no uncomfortable bending and turning of the hand when putting the cast on.
This research paper shows the amazing advantages 3D printing can have in the medical world. In further research we can look into new ways of connecting the parts of the cast, making it seamless and even easier to wear under clothes. Another new idea would be to add slots in the top and bottom, so the two parts stay fully secure and connected on the edges.

REFERENCES

[1] Nelson, F.R.T., Blauvelt, C.T.: *A Manual of Orthopaedic Terminology (Eighth Edition)*, W.B. Saunders, ISBN 9780323221580, 2015

[2] Valchanov, P.: 3D Printing in medicine – principles, applications and challenges. *Scripta Scientifica Vox Studentium,* Vol.1, pp.18-22, 2017

[3] Chen, Y., Lin, H., Yu, Q. Zhang, X., Wang, D., Shi, L., Huang, W., Zhong, S.:Application of 3D-Printed Orthopedic Cast for the Treatment of Forearm Fractures: Finite Element Analysis and Comparative Clinical Assessment, *BioMed Research International*, pp.1-12, 2020

[4] Waldburger L., Schaller R., Furthmüller C.: 3D-Printed Hand Splints versus Thermoplastic Splints: A Randomized Controlled Pilot Feasibility Trial, *International Journal of Bioprinting*, Vol.8, No.1, 2022

[5] Cucinotta F., Raffaele M., Salmeri F.: A stress-based topology optimization method by a Voronoi tessellation Additive Manufacturing oriented, *The International Journal of Advanced Manufacturing Technology*, Vol.103, pp.1965–1975, 2019

[6] https://all3dp.com/2/3d-printed-cast-the-most-promising-projects/

[7] Chen, Y., Lin, H., Zhang, X., Huang, W., Shi, L., Wang, D.: Application of 3D-printed and patient-specific cast for the treatment of distal radius fractures: initial experience, *3D Print Med*, Vol.8, 2017

[8] Waldburger, L., Schaller, R., Furthmüller, C., Schrepfer, L., Schaefer, D., Kaempfen, A.,: 3D-Printed Hand Splints versus Thermoplastic Splints: A Randomized Controlled Pilot Feasibility Trial. *International Journal of Bioprinting*, Vol.8, 2021

[9] https://www.dezeen.com/2013/06/28/cortex-3d-printed-cast-for-bone-fractures-jake-evill/

[10] https://competition.adesignaward.com/design.php?ID=34151#:~:text=Osteoid%20medical%20casts%20are%20made,to%20the%20Osteoid%20medical%20cast.

[11] Harrison, A., Lin, S., Pounder, N., Mikuni-Takagaki, Y.: Mode & mechanism of low intensity pulsed ultrasound (LIPUS) in fracture repair, *Ultrasonics*, Vol.70, pp.45-52, 2016

[12] https://activarmor.com/

[13] Farhan, M., Wang, J., Bray, P.: Comparison of 3D scanning versus traditional methods of capturing foot and ankle morphology for the fabrication of orthoses: a systematic review, *Journal of Foot and Ankle Research*, Vol.14, 2021

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26 May 2022, Belgrade, Serbia

MACHINE SIMULATION OF ADDITIVE MANUFACTURING TOOL PATH

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Nikola VORKAPIĆ
Stefan MITROVIĆ

Abstract: *The paper presents the programming and program verification using machine simulation of additive manufacturing tool path in CAD/CAM and Vericut environment. A procedure for configuring and preparing of a virtual machine for several additive process simulations has been proposed. The paper analyzes the available programming software for generating G code from the STL file as well as the possibility of simulating the virtual machine when working according to the generated program.*

Keywords: *additive manufacturing, machine simulation, CAD/CAM*

1. INTRODUCTION

Industry 4.0 has an initiative that aims to digitalize industrial manufacturing via the exploitation of innovative technologies [1]. In this regard, this paper will present the possibilities of applying the machine simulation of additive manufacturing processes in the era of Industry 4.0. The machine simulation of the additive manufacturing tool path aims to configure the digital twin of the machine for additive processes and simulate its work. Whatever happens on screen during simulation, will also occur identically on the real machine for additive processes.

Additive technology (AT) has emerged as a key enabling technology, with its ability to shorten product design and development time. AT is used for quick fabrication of physical models, functional prototypes and small series of parts directly from CAD models [2,3]. Rapid prototyping is used in a variety of industries to fast fabrication of parts, and representation before final realization or commercialization [4]. The main advantage of rapid prototyping technologies is that almost any shape can be produced.

The application of new additive technologies is based on models STL models of prototypes that will be build. This paper discusses two additive technologies: Fused Deposition Modeling - FDM and Laser Metal Directed Energy Deposition – Laser DED in terms of program preparation and its verification by simulation of material addition, i.e. machine simulation for these procedures.

Simulation is a key technology for program verification. Machine simulation and digital twin are the primary simulation-based approaches in the context of the Industry 4.0.

2. OUTLINE OF CONSIDERED ADDITIVE MANUFACTURING PROCESSES

Within this paper, the machine simulation of additive manufacturing machines based on the FDM (Fused Deposition Modelling) and Laser DED (Direct Energy Deposition) methods will be considered.

2.1. Fused Deposition Modeling - FDM

Fused deposition modeling (FDM) is one of the most widely used additive fabrication technologies. FDM is the same as fused filament fabrication (FFF), but the term "Fused deposition modeling" and the abbreviated "FDM" were trademarked by Stratasys in 1991, creating the need for a second name [5].

A plastic filament is unwound from a coil and supplied as a material to an extrusion nozzle, which moves along the programmed path of material addition. The possible movements of the nozzle are defined by the machine's own kinematic configuration. The nozzle is heated to melt the plastic, has closed-loop temperature control and is coupled with a mechanism which allows the deposition of the melted plastic to be turned on and off. As the nozzle is moved over the table in the active layer, following the programmed path, it deposits extruded plastic, thus forming each layer. FDM approach demands fully controlled extrusion of material through a nozzle. Two extrusion heads are often used so that support structures can be fabricated from a different material to facilitate part cleanup and removal, Fig.1.

FDM 3D additive machine is a type of a CNC machine that has 3 axes of movement and usually implements Cartesian (serial) or DELTA (parallel) mechanisms, although machines with hybrid kinematics are also possible. This paper considers Velleman Vertex K8400 additive manufacturing machine – 3D printer with 3-axis Cartesian serial kinematics.

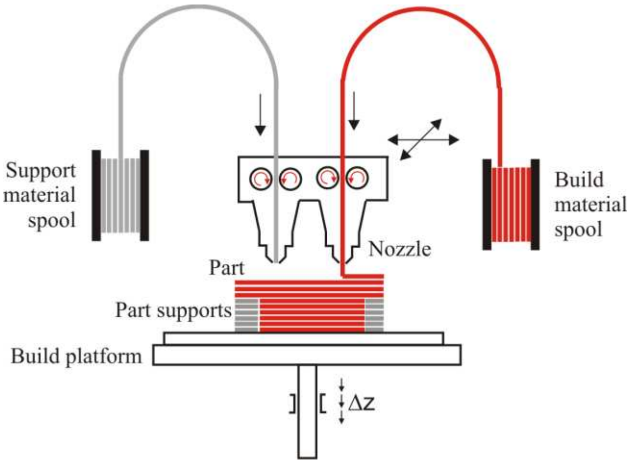

Fig.1. Schematic of FDM system

2.2. Laser Metal Directed Energy Deposition (DED)

Directed energy deposition (DED) is a group of AM processes that adds material alongside the heat input simultaneously. The heat input can either be a laser, electron beam, or plasma arc, while the material feedstock is either metal powder or wire [6]. This paper discusses laser and powder DED processes. A schematic of the laser powder DED process is shown in Fig. 1.

Powder DED machines often have powder-feeding gas blown together with the powder from the nozzles, thereby sheathing the melted region, and reducing the oxidization rate. Powder DED systems can use single or multiple nozzles to eject the metal powders [6].

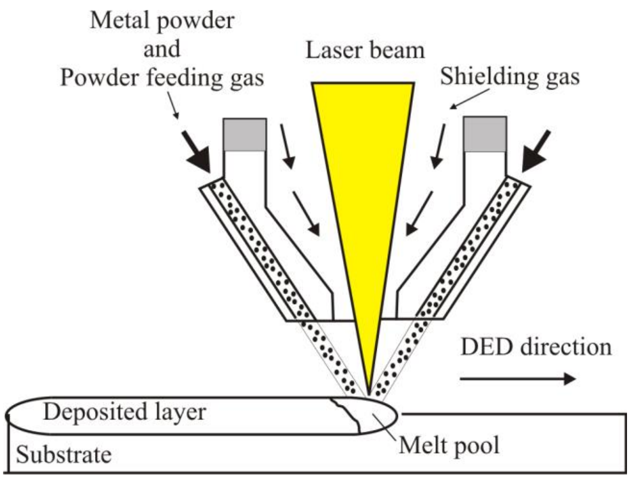

Fig.2. Schematic of a Laser powder DED process

Phillips has taken the innovative laser metal deposition technology of Meltio, and integrated it with the Haas CNC vertical machining centers, bringing the best value of additive hybrid machines to the market [7]. Supported Haas Machine Models are Haas VF Series, Haas UMC Series and Haas TM series. These machines can combine benefits from both additive and subtractive technologies. In this regard, the real challenge is the simulation of their work, which can be realized in the Vericut environment.

This opens the access to hybrid manufacturing processes that include additive and subtractive operations. Additive processes allow increased design flexibility, customization and part complexity, while subtractive processes enable higher production speeds, improved accuracy and surface finish [8]. Figure 3 shows a metal powder directed energy deposition (DED) process which can be combined with a multi-axis CNC milling process.

Fig.3. Laser DED extruder in a testing setup in a Haas VF series CNC machine [8]

3. CONFIGURING VIRTUAL MACHINES FOR ADDITIVE MANUFACTURING

The simulation of additive manufacturing machines and processes, in the era of Industry 4.0, is one of the most important verification steps prior to the actual production. This section will show procedures and examples of configuring virtual machines for additive manufacturing using available software environments (PTC Creo and Vericut).

3.1. PTC Creo

Most CAD/CAM systems are used for the simulation of the subtractive technologies, simulating virtual machine tool along a given tool path, while offering no similar alternatives for additive manufacturing.

In contrast, CAD /CAM system PTC Creo has a module for Additive Manufacturing, but it must be used in an indirect way, by configuring the machine for additive manufacturing as an equivalent milling machine with the same kinematics [9].

This paper presents the configuration of an additive manufacturing machine Velleman Vertex K8400 [10,11]. The configured virtual machine offers a virtual prototype with graphic structural elements that move as a rigid body system, aiming to be used in the simulation of the tool path [12]. All kinematic connections between structural elements of the virtual prototype must be defined in accordance with the real machine. The required kinematic connections for the considered 3-axis Velleman Vertex K8400 are three translations with slider and/or cylinder connection type, Fig.4.

During configuring of the complete virtual model of the machine, based on the available machine components [11], it is necessary to define the kinematic connections for all the moving parts. Next, need connect the coordinate systems of the workpiece, the tool with coordinate systems on virtual machine within the used PTC Creo 8.0. On virtual machine tool need to define the coordinate system MACH_ZERO, on the machine table and TOOL_POINT on top of the nozzle (Fig. 4b). Also, workpiece and tool have the same coordinate systems. By matching the appropriate coordinate systems of tool and workpiece with coordinate systems on virtual machine is prepare a set-up for simulation [12]. The virtual machine prepared in this way is ready for the needs of simulation according to the programmed tool path within the layer, which will be specified in section 5.

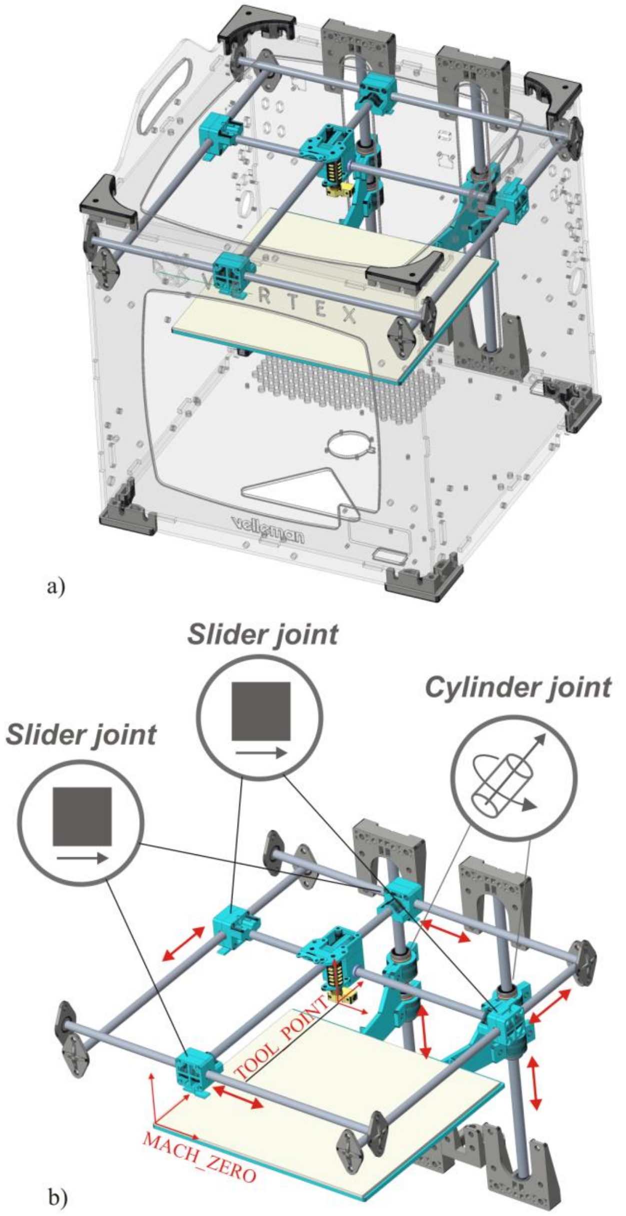

Fig.4. Virtual machine Velleman Vertex K8400 with defined kinematic connections and coordinate systems

3.2. Vericut

Vericut provides CNC machine simulation according to a given program, program verification and process visualization. Vericut now offers the Additive module that provides CNC machine simulation for directed energy deposition (DED), laser sintering, 3D printer and powder bed layups from their build files, wire-fed additives, thermo-plastic composite additives, welding, and other layup processes that add material [13].

A very important advantage of the simulation is collision detection between the expensive machine elements and the additive part being built [13].

Vericut uses G-code as one of its basic inputs, so to simulate an additive technology operation, one of the existing machines from the Vericut library that supports additive technologies can be selected, or a new machine can be configured.

To configure a new virtual machine in the Vericut environment, it is necessary to define the machine's kinematics – type and order of joints/axes according to the structural formula. For example, the Haas VF3 machine has a kinematic structure (X'Y'OZ), Fig.5.

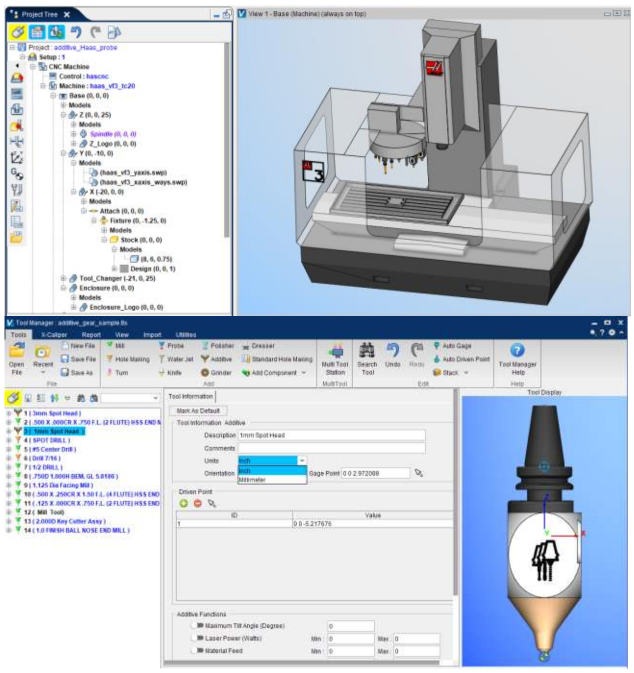

Fig.5. Selected virtual machine Haas vF3 and Laser DED extruder

The basic structure of the machine tool in Vericut consists of a BASE, TOOL, and STOCK. The configuration of the virtual machine starts from the base (O), as a fixed component. The vertical translational axis Z (Z Linear) was first added to the base, on the tool side. The horizontal translational axis Y '(Y Linear) was first added to the base in order, and then the horizontal translational axis X' (X Linear) was added to it, on the workpiece side.

On the spindle that moves along the Z-axis, there is the main spindle (Spindle) and a tool (Tool), which completes the kinematic structure of the machine. The hierarchical tree structure of the Haas VF3 machine is shown in Fig. 5. The machine has the name *haas_vf3_tc20* with control *haascnc*. This machine supports additive technologies and will be used as an example for simulation of additive technology in section 5.2.

4. PROGRAMMING OF MACHINES FOR ADDITIVE MANUFACTURING

Programming of machines for additive manufacturing can be realized using various specialized software, such as Slic3r, Replicator G, Catalyst EX, Repetier-Host, and others. These programs represent an interface for communication with additive manufacturing machines. The input into these programs is a 3D model file, upon which we prepare additive layers and the required paths for material addition. Such programs usually allow [10]: (i) 3D model display; (ii) model scaling to the desired size; (iii) model orientation in the workspace; (iv) automatic or manual basing of the model when several parts are produced at once; (v) slicing and forming of additive layers; (vi) layer addition simulation and display of each layer; (vii) G- code generation for the specified machine.
In this paper, the Slic3r software was tested as a programming software of the considered machines for additive processes. Slic3r translates digital 3D models into instructions that are understood by a 3D printer (G-code). It slices the model into horizontal layers and generates suitable paths to fill them. Slic3r accepts the following 3D model files types: STL (Stereo Lithography), OBJ, Additive Manufacturing File Format (AMF), while 3MF is an XML-based file format, similar to AMF [14].
A typical procedure for additive manufacturing includes the following stages: (1) obtain the model in STL format, (2) load model into software, (3) set the parameters for 3D additive manufacturing (print, filament, printer), (4) export to G-code (5) simulate 3D additive manufacturing, (6) build prototype on the machine.
The first example for programming additive processes was tested on the example of the champions league cup model in pendant form, given in STL format, Fig.6.

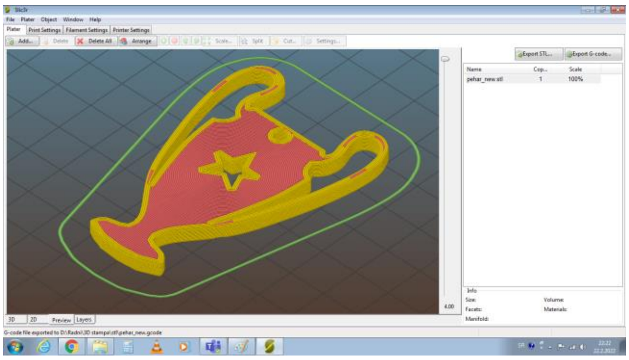

Fig.6. The example of the champions league cup in pendant form in slic3r environment

For this example, machine simulation was prepared in CAD/CAM system PTC Creo (section 5.1), and finally this part was made on Velleman Vertex K8400 machine for additive manufacturing using FDM. Model for the first example is prepared in PTC Creo 8.0 and exported in the STL format that was loaded into Slic3r, where G-code is obtained for additive manufacturing. Prior to generating the G-code – print, filament and printer settings are adjusted. After generating the G-code, options are available for simulating the addition of material with the possibility of displaying toolpath for each individual layer.
The second example of programming additive processes, utilizing laser directed energy deposition (DED), is prepared for CNC machine simulation, Fig.7. Here also, the model is produced in PTC Creo, exported in STL and loaded into Slic3r, where the G-code is obtained for additive manufacturing. This example was checked in Vericut environment.

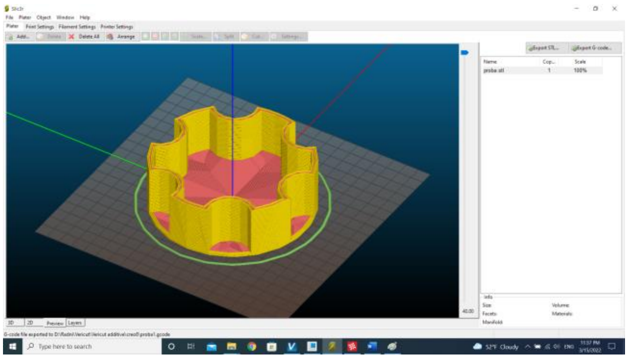

Fig.7. The second example of CNC machine simulation for laser directed energy deposition

5. MACHINE SIMULATION AND TOOL PATH VERIFICATION

This section presents a machine simulation of additive manufacturing for two considered methods: FDM and DED in two different environments (PTC Creo and Vericut).

5.1. Machine Simulation of Additive Manufacturing in Creo

An example of programming additive processes for FDM was tested on the example of the champions league cup in pendant form and printed on Velleman Vertex K8400.
CAD/CAM system PTC Creo can simulate additive manufacturing in an indirect way. The configuration of the considered additive machine Velleman Vertex K8400 is shown in section 3.1. The configured machine can move along the tool path for each individual layer. The simulation of the last layer was chosen for the illustration.
To obtain the toolpath (nozzle path) in additive processes, it is necessary to convert the nozzle path into G code, using appropriate software, Slic3r in this case, Fig.8. Obtained G-code can be converted into DXF file using CIMCO software. After that, the DXF is loaded into PTC Creo, where it is saved as a part, including nozzle path as a curve. This part is used in the CAM Manufacturing module (CAM-MFG), where the nozzle path serves to generate tool paths for simulation. During the simulation, the CAD model of the complete virtual machine can be loaded in PTC Creo environment, as shown in Fig.8, and Fig.9.

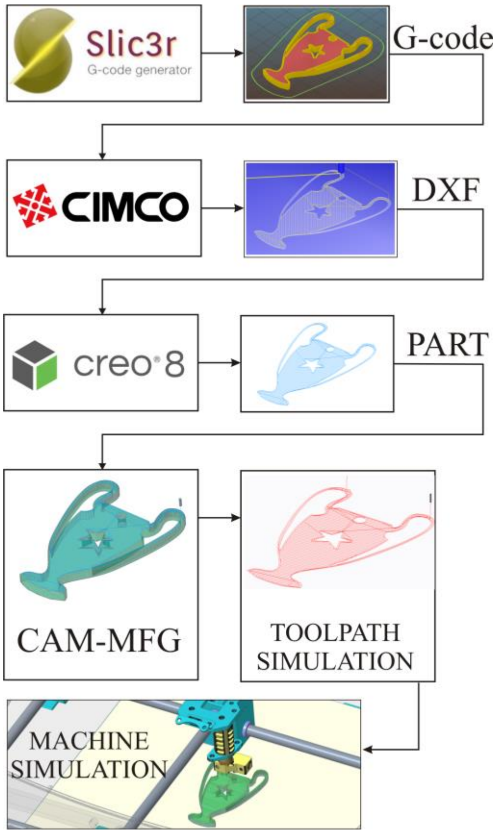

Fig.8. Procedure for indirect machine simulation of additive tool path on each layer

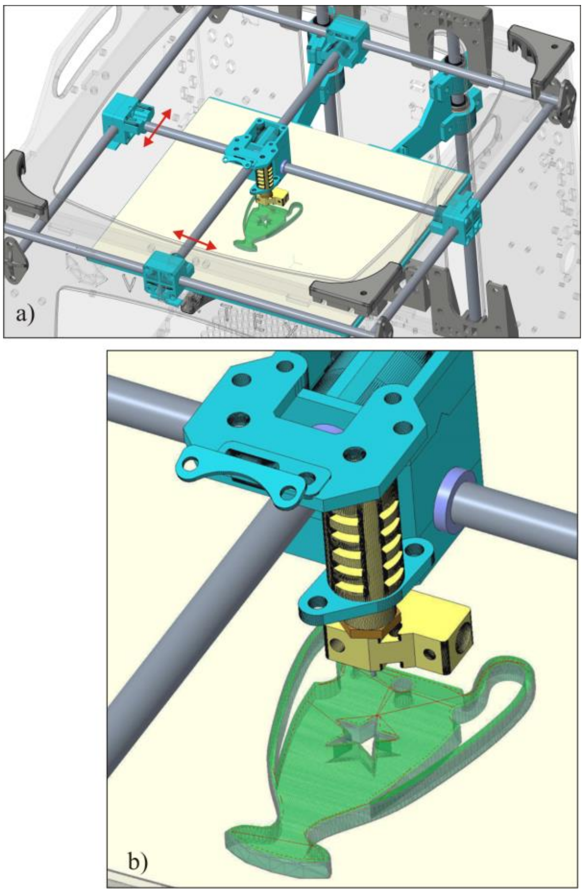

Fig.9. Machine simulation according to the given tool path within the last layer in PTC Creo environment

An illustration of the work done on Velleman Vertex K8400 during 3D printing of the first example is shown in Fig.10.

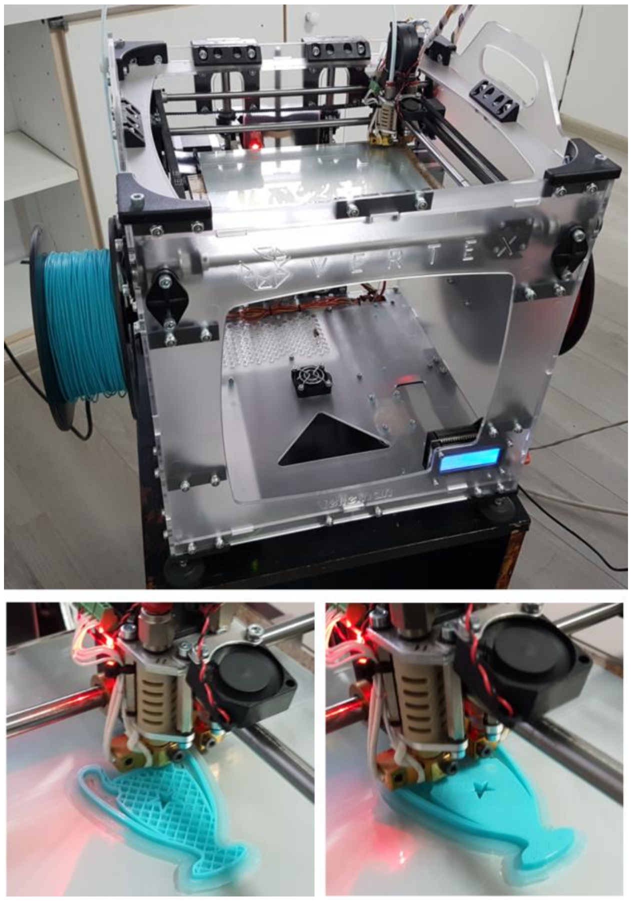

Fig.10. Velleman Vertex K84000 during the printing of model champion league cup in pendant form in STL format

5.2. Machine Simulation of Additive Manufacturing in Vericut

Simulation of the virtual machine tool in the VERICUT environment, according to the given program, allows the simulation of the operation of the machine based on G-code [15]. Virtual machines can be loaded from the available library or configured from scratch by the user, as explained in Section 3.2. The following is a procedure for additive technology simulation based on G-code with an example of adding material by directed energy deposition (DED). The project hierarchical tree of Vericut has already been discussed in the description of the virtual machine configuration, and now the other parts it contains are presented, referring to the basic tools needed to prepare a simulation project according to the given program, Fig.11, with specifics that are characteristic for additive technology.

At the beginning, it is necessary to choose the control system and the virtual machine to perform the simulation. For example, in this paper, the chosen machine is haas_vf3_tc20 with its control haascnc.

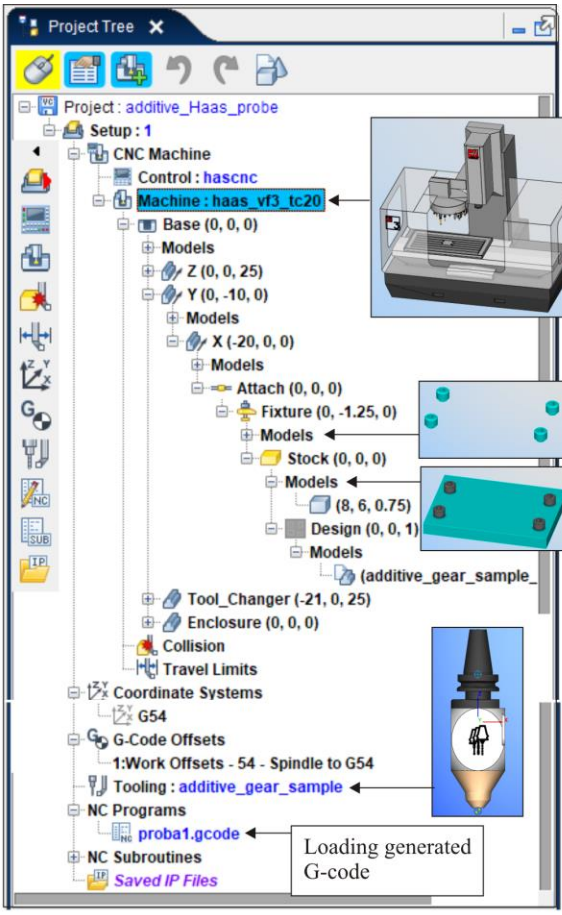

Fig.11. VERICUT project hierarchical tree, an example of for additive technology

To continue with the definition of the simulation project, in this case, for additive technology, it is necessary to define: (i) stock as the platform on which the model will be based, and which is here connected to the worktable by means of a fixture; (ii) coordinate system (Program Zero Point), here G54, (iii) zero-point position adjustment on the virtual machine (G-code Offsets), (iv) tools which are used for additive technology (Laser DED extruder) and (v) G-code for additive technology.

In order to connect the virtual machine to the zero point of the program, it is necessary to select the appropriate offset of the G-code. Work offset was chosen from Spindle to CSYS Origin-G54.

G-code is prepared in software for additive manufacturing (Slic3r), and loaded in Vericut environment for simulation. When all the previously mentioned stages for the preparation of the simulation project are completed, the G-code is loaded and the additive technology is simulated, Fig.12.

The simulation display of the virtual machine operation can be organized in several views, namely: Stock (workpiece)-view, where we can see the material being added layer by layer; Machine Base (Machine) - view, where the simulation of adding material can be followed on the virtual machine.

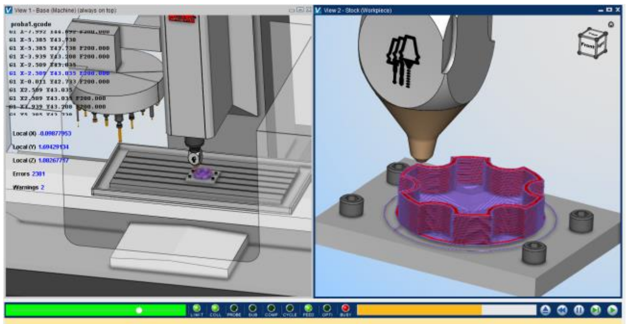

Fig.12. Machine simulation of Haas vF3 virtual vertical machining center operation on example of additive technology

During simulation, its speed can be controlled using the slider on the bottom-left of the screen. Also, the display of the G-code can be included, that also marks the line being executed. The final result of the simulation and the look of the obtained part is shown in Fig.13.

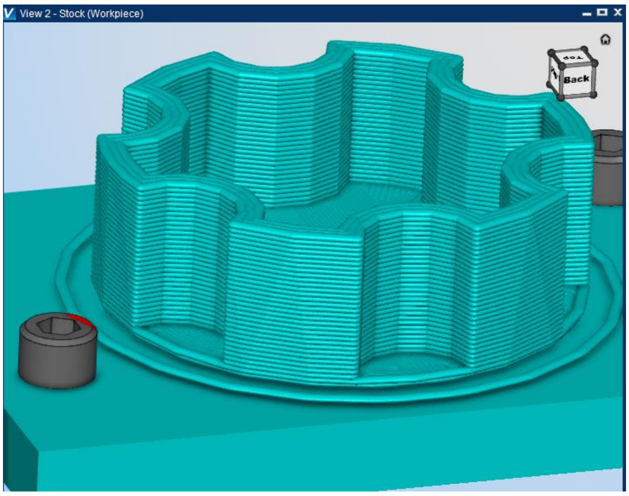

Fig.13. Finished simulation example of additive technology

6. CONCLUSION

This paper provides an overview of programming and program verification using machine simulation in two environments for additive technology. Two methods for rapid prototyping by adding material were considered: fused deposition modelling and laser direct energy deposition.

In the age of Industry 4.0, an important research direction is digitization and virtualization of processes, enabling better verification and process monitoring.

Currently, there is ongoing research in the field of adding metallic materials in combination with milling, the so-called. hybrid manufacturing, uniting additive and subtractive technology.

The importance of machine simulation for additive processes refers to the detection of possible collisions of various extruders with machine parts or the part to be made, thus gaining a higher degree of safety for people and equipment.

Our further research relates to the configuration of new virtual machines that combine additive and subtractive technologies – virtual hybrid manufacturing.

ACKNOWLEDGMENT

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REFERENCES

[1] Zivanovic, S., Slavkovic, N.: Programming of machine tools and robots for machining using STEP-NC in the era of Industry 4.0, Keynote Lecture, *Proceedings of the 15th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI 2021*, 28-29 May, University of Banjaluka, Faculty of Mechanical Engineering, pp. 3-26, 2021.

[2] Pham, D., Dimov, S.: *Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling*, Springer Verlag, London, 2001.

[3] Pham, D., Dimov, S.: *Rapid prototyping and rapid tooling– the key enablers for rapid manufacturing*, Proceedings of the Institution of Mechanical Engineers, Part C, 217, pp 1–23, 2003.

[4] Gibson, I., Rosen, D. and Stucker, B.: *Additive Manufacturing Technologies, 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, 2nd Edition, Springer New York Heidelberg Dordrecht London, 2010.

[5] https://all3dp.com/2/fused-deposition-modeling-fdm-3d-printing-simply-explained/, Craftcloud, Accessed on 2022-03-27.

[6] Harbaugh, K., McClain, A.: 3D printing of metals in rapid prototyping of biomaterials: Techniques in additive manufacturing, In: Rapid Prototyping of Biomaterials, Editor Roger Narayan, pp.17-40, Elsevier Ltd, 2020.

[7] https://meltio3d.com/phillips-additive-hybrid-haas-cnc-meltio/, Phillips Additive Hybrid integrates Haas CNC with Meltio, Accessed on 2022-03-22.

[8] Weaver, J., Jones, J.: Characterization of high-deposition polymer extrusion in hybrid manufacturing, Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, August 13-15, The University of Texas at Austin, Austin, Texas, USA, 2018.

[9] Zivanovic, S.: Rapid prototyping and manufacturing for model of human head, *Proceedings of the 8th International Scientific Conference IRMES 2017-Machine elements and systems in energy sector Development of power production systems*, 07-09. September, Trebinje, Bosnia and Herzegovina, pp. 271-276, 2017.

[10] https://vertex3dprinter.eu/downloads/vertex-downloads/, VERTEX ORIGINAL (K8400), Accessed on 2022-03-26.

[11] https://github.com/Velleman/Vertex-CAD, Velleman Vertex-CAD, Accessed on 2022-03-26.

[12] Tabakovic, S., Zivanovic, S., Dimic, Z., Zeljkovic. M.: Programming of 3-Axis Hybrid Kinematics CNC Machine for Rapid Prototyping Using Subtractive and Additive Processes. *Journal of Mechatronics, Automation and Identification Technology*, Vol. 6, No. 4, pp. 16 – 21, 2021.

[13] https://www.cgtech.com/products/product-line/85-additive.html, VERICUT's Additive module simulates both additive and traditional machining (milling or turning) capabilities of new hybrid CNC machines, Accessed on 2022-03-22.

[14] https://slic3r.org/about/, Slic3r - Open-source 3D printing toolbox, Accessed on 2022-03-22.

[15] Zeljković, M., Tabaković, S., Živković, A., Živanović, S., Mlađenović, C., Knežev, M.: *Basics of CAD/CAE/CAM,* University of Novi Sad, Faculty of Technical Sciences, ISBN 978-86-6022-120-1, 2018.

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A NEW CONCEPT OF BELT GRINDER DESIGN WITH IMPROVED FRAME RIGIDITY

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Marija MATEJIC
Lozica IVANOVIC

Abstract: *For the purposes of this research two of the belt grinder concepts have been developed. The biggest attention is given to the rigidity of the belt grinder frame, functional and ergonomic aspects. After developing these two concepts, the CAD models have been made. Both concepts are evaluated through a couple of industrial design aspects. After evaluation, the prototype has been made and tested. All of the industrial design aspects were proven by prototype testing in real working conditions. At the end of the paper, the conclusions have been drawn and future research directions on this topic were given.*

Keywords: *belt grinder; industrial design; model evaluation; concept testing.*

1. INTRODUCTION

The machining accuracy and surface quality of such parts will be the key factors that ultimately determine the performance of the equipment. Grinding is usually the last step in the processing of complex profile parts. As a new grinding technology, abrasive belt grinding has the characteristics of low grinding temperature and high grinding efficiency, and has been widely used in precision grinding of complex surface parts [1-2]. Coated abrasive belts are used in the same speed range as bonded wheels, but they are not generally dressed when the abrasive becomes dull. Abrasive belt grinding is a kind of grinding tool with special form, which needs straining device and driving wheel and to make abrasive belt strained and moved at high speed, and under certain pressure, the contact between abrasive belt and work piece surface can help to realize the whole process of grinding and machining. Belt grinding is a rough machining procedure utilized on wood and different materials. It is commonly utilized as a completing procedure in industry. A belt, covered in rough material, is kept running over the surface to be handled so as to evacuate material or create the ideal finish. [3]

A compliant belt grinding resembles an elastic grinding in its operating principle, and it offers some potentials like milling, grinding and polishing applications [4]. The abrasive belt grinding process essentially is a two-body abrasive compliant grinding processes wherein the abrasive belt is forced against the components to remove undesired topographies, such as burrs and weld seams, to achieve the required material removal and surface finish [5]. Analogous to other abrasive machining processes, many process parameters in the belt grinding impact the material removal performance, which include cutting speed, loading belt tension, the force imparted, infeed rate, workpiece topographies, polymer wheel hardness, wheel geometry and belt topography features, e.g., backing material, grain composition, and grit size [6]. Material removal in the belt grinding process is determined by force distribution in the contact area between the workpiece and the elastic contact [7]. The effect of abrasive grain size on the material removal performances of the grinding surface was studied by theoretical modeling and grinding experiments. The results indicated that a smaller abrasive grain size of the abrasive belts led to smaller microscopic contour height and surface roughness of the ground surfaces, fewer curl chips, and more spherical chips [8].

The accurate prediction of the replacement time of abrasive belts can help not only improve the product quality but also reduce the cost. According to the analysis of displacement data, a new method for the prediction of abrasive belt wear states using a multiscale convolutional neural network based on transfer learning is proposed in the paper of the authors [9]. The experimental results show that this method can accurately predict the wear status of abrasive belts, with an average prediction accuracy of 93.1%. Also, authors [10] were investigating cutting force, single grain wear height and full-size grinding mileage verification experiments were conducted. The results indicated that the established model was in reasonable agreement with the experimental outcomes, which suggests that this model could be useful

in the industry to predict the wear process of abrasive belts.
The machine we designed and fabricated is used for grinding any shape of object like circular, rectangular and polygon. In our project the work abrasive belt is used to grinding the material. The abrasive belt is rotated by single phase induction motor. Hence our project namely adjustable belt grinder.

2. DEVELOPING BELT GRINDER CONCEPTS

In this study two belt grinder concepts were developed. The most influential factor in concepts developing was the belt grinder frame rigidity. The frame rigidity is necessary in order to get the best grinding results. Before the concept developing the main functions of the future product was determinated such as:

- the grinder work table must have ability to rotate from 0 degree to 180 degree,
- the work table must have adjustable height,
- the grinder must have ability to accept various sizes of grinding belts (papers),
- easy change of the grinding belts (papers)
- safety of operator must be fulfilled and
- future product must have enough rigidity.

After main functions the main part of grinder was listed:

- driving unit (electric motor),
- driving pulley,
- driven pulley,
- belt tensioning mechanism,
- grinder frame and
- work table.

Based on the previous statements two concepts was developed. One concept was based mostly on square pipes, while other was based on the combination of steel plates and square steel pipes.

2.1. Belt Grinder based on square steel pipes

The concept based on square steel pipes was imaged to be not expensive variant of the belt grinder. The basic sketch was made, and after that the CAD model was created. The proposal of the concept based on the steel square pipes was given in Fig. 1.

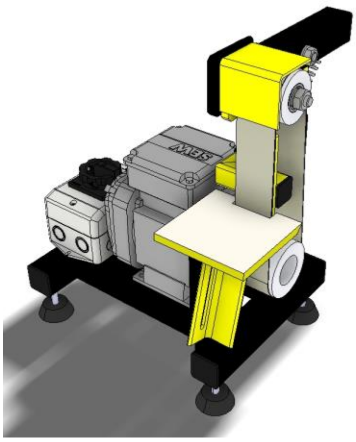

Fig.1. Belt grinder concept based on square steel pipes

The frame is designed as H letter to support the electric motor. Work table is connected to frame by using L-steel profiles, tension mechanism is based on lever which is tensioning the driven pulley by extension spring. Driven pulley has adjustable angle ability related to horizontal. The proposed concept is light in weight.

2.2. Belt grinder concept based on steel plates and square steel pipes

The belt grinder concept based on steel plates and square steel pipes was imaged to be a bit more expensive variant related to the previous shown concept. The basic sketch of the belt grinder was made, and after that the CAD model was developed. The proposal of the concept based on steel plates and square steel pipes was given in Fig. 2.

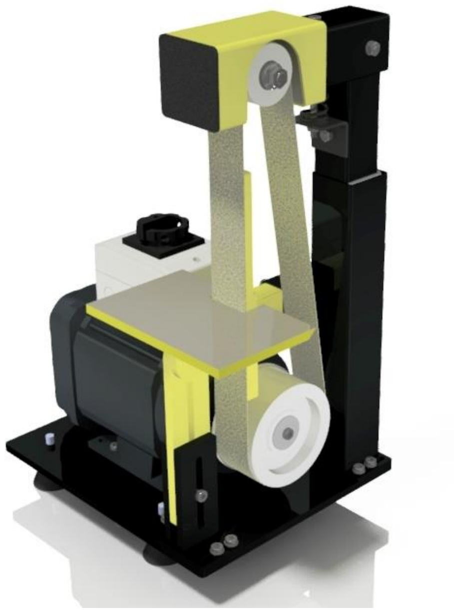

Fig.2. Belt grinder concept based steel plates and square steel pipes

The frame is designed as steel plate with adjustable holes for electric motor and machine leveling. Work table is connected to frame by steel plates cut on laser, tension mechanism is based on lever which is tensioning the driven pulley by compression spring. Driven pulley has adjustable angle ability related to horizontal. The proposed concept is no so light in weight.

3. EVALUATING OBTAINED SOLUTIONS

The evaluation of the both proposed solutions has been made. The comparison was made on: frame, work table, tensioning mechanism, adjusting abilities, belt changing abilities etc.

3.1. 3.1. Frame comparison

Frame of the solution 1 is shown in Fig. 3. The frame was done in shape of H letter and it consists of rectangular steel pipes with cross-section of 40x40x2 mm.

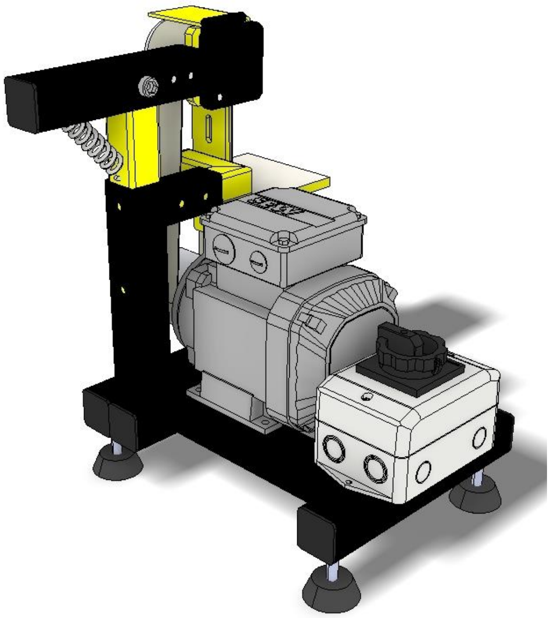

Fig.3. Frame of the solution 1

Frame of solution 2 was done from steel plate with 10 mm thickness. Steel plate was cut on laser cutting machine. Frame of solution 2 is shown in Fig 4.

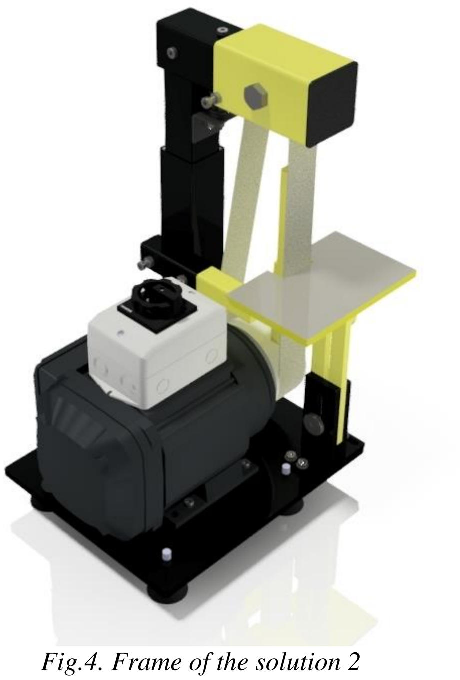

Fig.4. Frame of the solution 2

The frame of the solution 2 has much better rigidity related to the frame of the solution 1. Frame of the solution 2 is much easier to be made, but because of the bigger amount of the used steel it is more expensive than solution 1.

3.2. Work table comparison

Work table of the solution 1 is given in Fig. 5. The work table have the abilities which are requested in section 2. Two points of worktable rotation allows work table to be used for a variety of grinding operations.

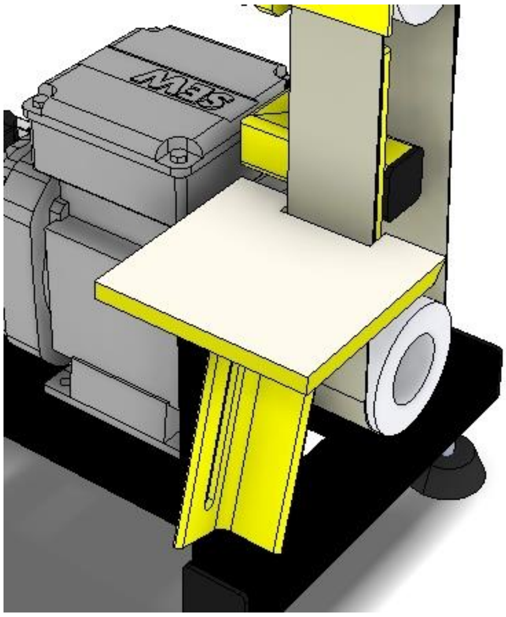

Fig.5. Work table of the solution 1

Worktable of the solution 2 is given in Fig. 6. The only difference between given worktables is in the rigidity. As worktable of the solution 1 uses L-profiles L40x40x4 which are much thinner related to the laser cut steel plates of 10 mm thickness in the solution 2.

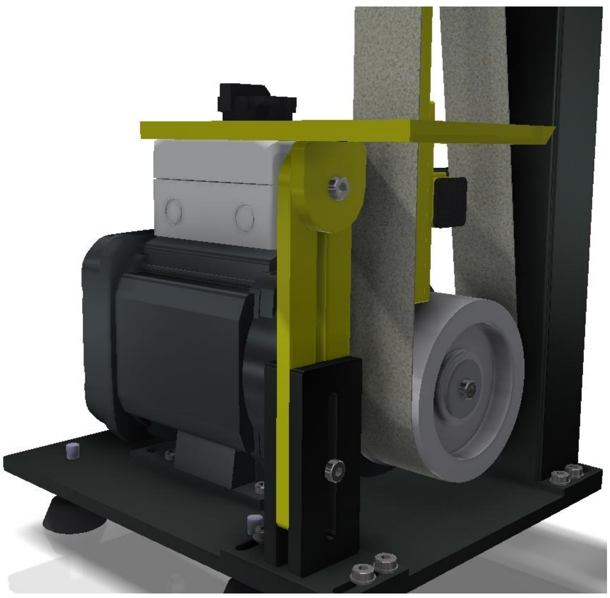

Fig.6. Work table of the solution 2

The advantage of worktable in solution 1 is a bit easier manipulating and adjusting of worktable angle because it relies on L profiles which are lighter in weight and easier for manipulation and adjustments.

3.3. Tensioning mechanism comparison

The tension mechanism of solution 1 is shown in Figure 7. Tension mechanism on this solution uses an extensions spring.

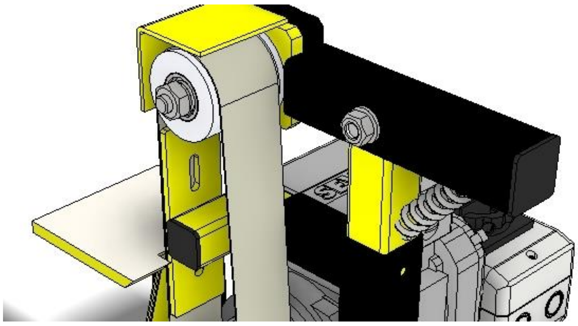

Fig.7. Tension mechanism of the solution 1

Tension mechanism of the solution 2 is given in Fig. 8. Tension mechanism of the solution 2 uses a compression spring.

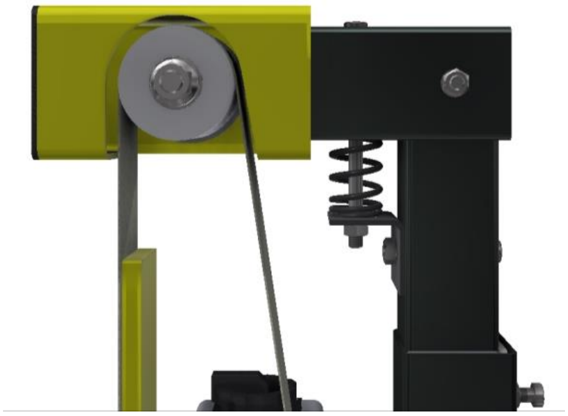

Fig.8. Tension mechanism of the solution 2

Both of the belt tension solutions are acceptable and durable. The second tension solution is a bit easier for usage because a less hand power is necessary for the grinding belt changing.

3.4. Adjusting abilities comparison

Adjusting abilities of the solution 1 are shown in figure 9.

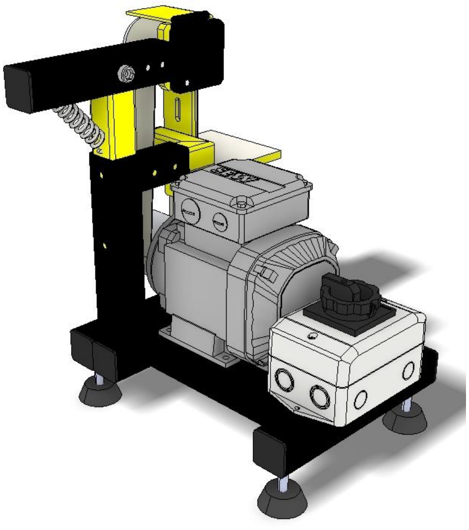

Fig.9. Adjusting abilities of the solution 1

In solution 1 the driven pulley can be adjusted by horizontal angle, the belt supporting plate can be adjusted, the height of the tension mechanism can be adjusted and worktable as well.
In Fig. 10. are shown adjusting abilities for the solution 2.

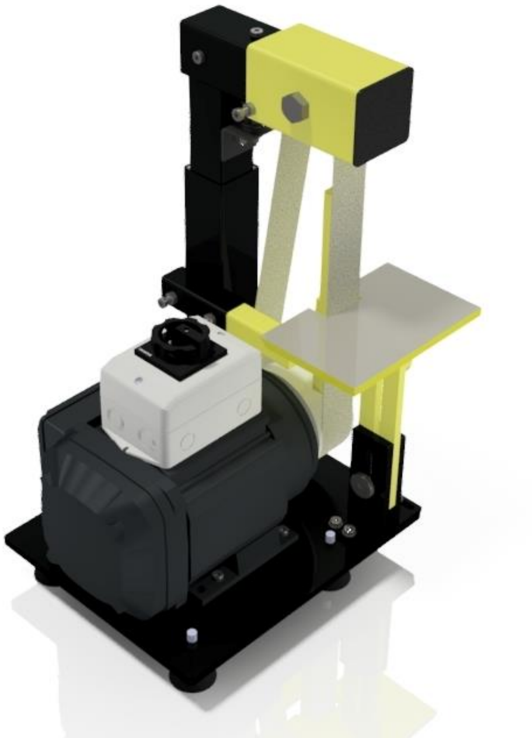

Fig.10. Adjusting abilities of the solution 2

Solution 2 has 2 advantages. Frist one is that whole vertical pillow which carries tension mechanism can move back and forward and it can use a variety of pulley sizes. The linear movement of the work table is done on the solution 2 as well.

3.5. Belt changing ability comparison

Belt changing ability was very nice solved on both solutions. a bit more difficult was belt changing on the solution 2 because the tension mechanism in lighter in mass and more hand power is required to push the tension mechanism down.

4. TESTING CHOSEN PROTOTYPE

For the prototype manufacturing the solution 2 has been selected. After manufacturing of the parts belt grinder was assembled. Assembled belt grinder is given in Figure 11-14.
After belt grinder assembling a couple of functional tests has been performed. The following test was done: changing the belt, adjusting machine for the 3 various belt types (with 3 different lengths), the operation of drill sharpening was performed and operation of preparing parts for welding.

Fig.11. Assembled belt grinder

Fig.12. Assembled belt grinder

The test for changing grinding belt went very fast and with no difficulties because the compression spring was chosen by catalogue force for belt tensioning.

Fig.13. Assembled belt grinder

Test of machine adjustment for different grinding belts length was done with some difficulties. The main difficulty was determining of tensioning mechanism height. A scale on the telescopic mechanism pipe would be very useful for implementation.

Fig.14. Assembled belt grinder

For drill sharpening the measurement of the table angle was done. Drill sharpening went without difficulties. Last test was done on preparation parts for welding in order to get chamfered edges. After chamfering edges on the belt grinder all of them was the same and uniform size so the test was successful.

5. CONCLUSIONS

In this paper two belt grinder concepts was developed. Both concept was developed in details with CAD models. After CAD models developing the evaluation of the obtained results was performed. Evaluation process gave advantage to the second belt grinder concept which is based on steel plates and steel square pipes. The chosen concept has much higher rigidity related to the concept which is based just on square steel pipes. After evaluation the belt grinder was manufactured and tested. Testing was performed on drill bits sharpening and welding parts edges preparation. The both tests was completed successfully. In the next step of this research the belt speed variation and control will be implemented.

REFERENCES

[1] Wang Yajie.: Precision abrasive belt grinding research based on contact theory [D]. Chongqing University, 2015.

[2] Huang Zhi, Huang Yun.: The principle and application of abrasive belt grinding. Machinist Metal Cutting, (24):28-30, ISSN:1000-7768, 2008.

[3] S. Mezghani, M. El Mansori, E. Sura.: Wear mechanism maps for the belt finishing of steel and cast iron [J]. Wear, 267:132-144, ISSN: 0043-1648, 2009.

[4] Wang, S.; Li, C.: Application and development of high-efficiency abrasive process. Int. J. Adv. Sci. Technol., 47, 51–64. ISSN: 2005-4238, 2012.

[5] Pandiyan, V.; Tjahjowidodo, T.: In-process endpoint detection of weld seam removal in robotic abrasive belt grinding process. Int. J. Adv. Manuf. Technol., 93, 1699–1714, ISSN 0268-3768, 2017.

[6] Ren, X.; Cabaravdic, M.; Zhang, X.; Kuhlenkötter, B. :A local process model for simulation of robotic belt grinding. Int. J. Mach. Tools Manuf., 47, 962–970, ISSN 0890-6955, 2007.

[7] Zhang, X.; Kuhlenkötter, B.; Kneupner, K.: An efficient method for solving the Signorini problem in the simulation of free-form surfaces produced by belt grinding. Int. J. Mach. Tools Manuf., 45, 641–648, ISSN 0890-6955, 2005.

[8] Wang, N., Zhang, G., Ren, L. and Yang, Z.: Analysis of abrasive grain size effect of abrasive belt on material removal performance of GCr15 bearing steel. Tribology International, 171, p.107536, ISSN 0301-679X, 2022.

[9] Zhihang Li, Qian Tang, Sibao Wang, Penghui Zhang, A deep transfer learning method for monitoring the wear of abrasive belts with a small sample dataset, Journal of Manufacturing Processes, Volume 74, 374-382, ISSN 1526-6125, 2022.

[10] He, Z., Li, J., Liu, Y., & Yan, J.: Single-grain cutting based modeling of abrasive belt wear in cylindrical grinding. Friction, 8(1), 208-220, ISSN 2223-7690, 2020.

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IMPROVEMENT OF THE EDUCATION PROCESS OF MECHANICAL ENGINEERING STUDENTS USING SCALE MODELS

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Abstract: *The development of 3D modeling software has greatly influenced the perception of mechanical engineering students. Instead of thinking about machine elements and assemblies and presenting them in 2D, today's students are educated from the beginning of their studies so that they realize their ideas in 3D, i.e., in space. Therefore, a problem arises when students need to understand the way certain machines and devices work through sketches, diagrams and technical documentation that are in university textbooks and scripts. For this reason, teaching aids that are in laboratories in physical forms - either in the form of a scale model or in real size - are becoming increasingly important. This paper will present a scale model of a continuous transport device, which is located within the Laboratory for Mechanical Design, Transport Systems and Logistics, Department of Mechanization and Design Engineering, Faculty of Technical Sciences in Novi Sad. First, a brief overview of the application of the model in the teaching process is given, and then four devices of continuous transport are presented, whose computer and physical model was formed, as well as the corresponding power transmissions and DC drive motor that drives all conveyors. At the end of the paper, it is pointed out that the quality of teaching has significantly improved, through a concrete example of a physical model of a device for continuous transport.*

Keywords: *quality of teaching; improving the teaching process; model*

1. INTRODUCTION

Modern education has a very important role in the transformation of society towards the knowledge economy. In the realization of this role in the coming period, the development of education in several basic directions can be expected. The key direction refers to the application of new technological achievements in the educational process, but also new methods in teaching. In addition, the role of the professor is changing, who, in addition to the lecturer, should also be a motivator, associate and advisor to the student.
One of the methods of demonstration in teaching is to show everything that can be perceived perceptually, such as static objects (images, models, schematic drawings), but also dynamic phenomena such as in this case the movement of conveyor elements, tracking the power transmission scheme, from the drive motor to the drive elements of the conveyor, etc.
Since the inception of didactic, a special understanding of teaching in the form of the so-called didactic triangle is present. Didactic triangle contains three basic elements, or three basic components of the teaching process, and they are student - teacher – content [1]. However, from the modern point of view of pedagogy, as well as other sciences, this understanding of teaching is one-sided and it is necessary to expand the triangle by adding teaching techniques, which forms a didactic quadrangle **Error! Reference source not found.**, fig.1.

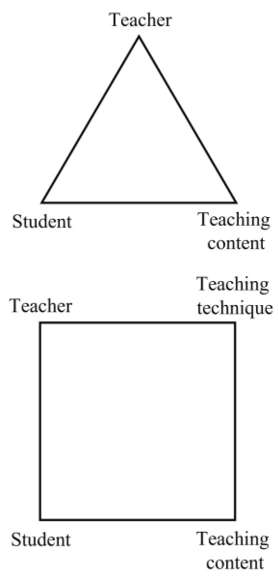

Fig. 1. Didactic triangle and tetragon

For students of technical sciences, and thus mechanical engineering, as one of the teaching techniques, without which modern education is inconceivable, is the use of computers to form 3D models of machine elements, machines and devices, as well as for various forms of calculation. This creates a virtual prototype of the device, whose possibilities are very diverse. Simulations of individual states can be performed, with monitoring of the behavior of the device elements (kinematic quantities, stress state and deformation of the elements, heating) that may occur in reality. For additional understanding of functioning, it is useful to form a physical model. Through the formation or assembly of elements of the physical model, students together with teachers notice all the difficulties that staff face in reality when assembling real devices, which is not written enough in textbooks. These observations should certainly encourage students, future engineers and designers to incorporate in future design work the experience they will gain in forming a physical model of some machine system. In this way, students are directly acquainted with the importance of choosing the right way to place and order the elements on the shafts (circlips, bearings, bushings, seals, keys, pulleys, gears), the right choice of tolerance and respect of the same, chamfering the edges of shafts and housings, the importance of shaft alignment, the function of tensioning devices in pulling elements of the conveyor, the importance of stiffness and load-bearing capacity of the supporting structure, as well as precisely defining the position of the connection of device elements to the structure, etc. These aspects are theoretically covered in studies, but in this way, by direct participation in the work of assembly / disassembly, these phenomena are certainly better understood and adopted by the student.

For that purpose, first a 3D computer model was formed, and then a physical model of the transport system, which consists of several continuous transport conveyors. Components of machine elements were chosen from the company Mädler [3] and the components of the supporting structure were chosen from the company MayTec **Error! Reference source not found.**. All components were later donated from mentioned companies.

2. 3D COMPUTER AND PHYSICAL MODEL OF THE TRANSPORT SYSTEM

First, a 3D model of the complete transport system was formed. The model of the transport system is formed by four conveyors, corresponding power transmissions and a drive unit with consisted of a DC motor with a planetary gearbox, fig 2. Marked elements on the figure are defined in Table 1. The physical model can be seen in fig 3.

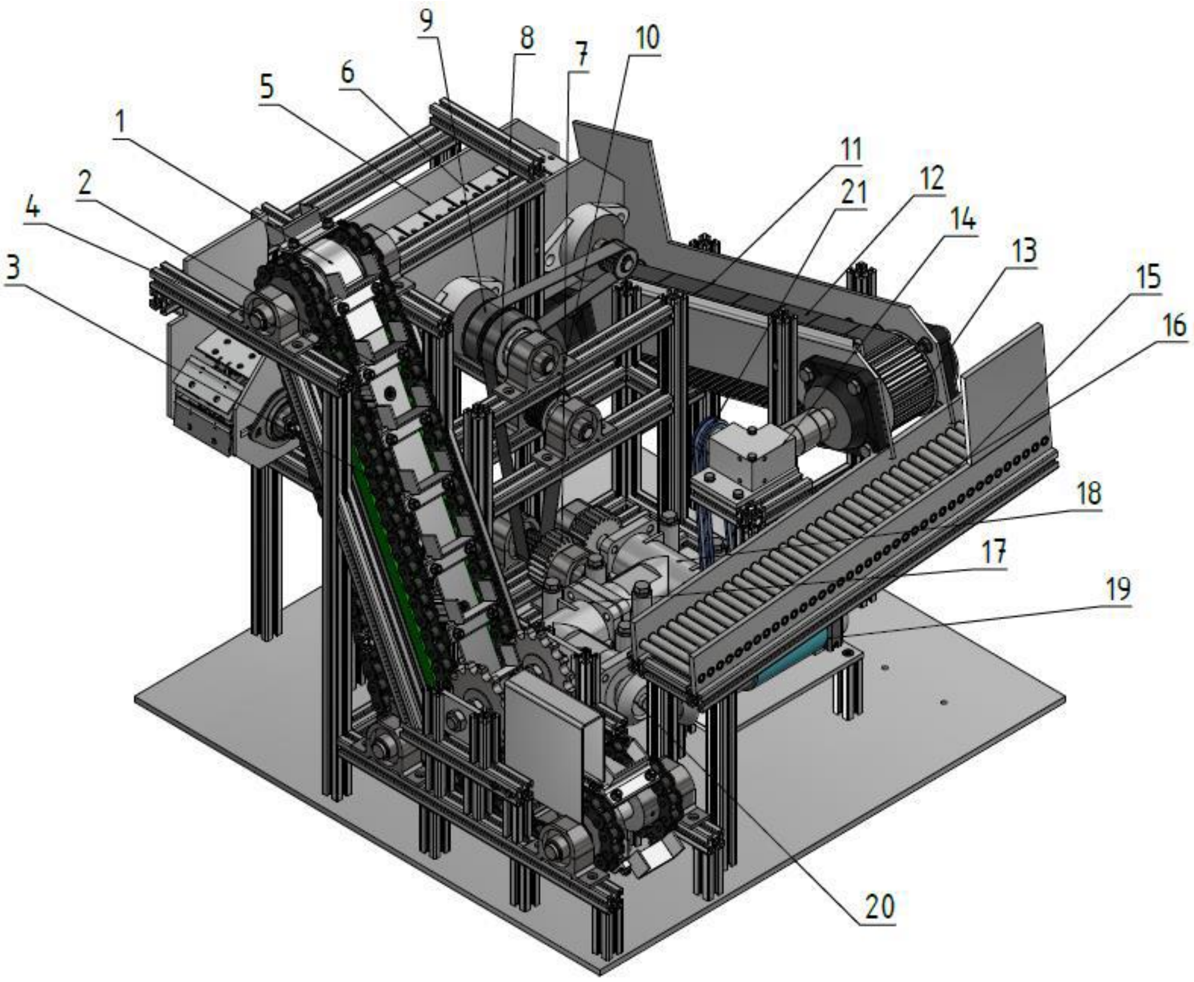

Fig. 2. 3D model of the transport system

Table 1. Elements of the transport system

No	Item	Explanation	No	Item	Explanation
1.	Flight (scraper) conveyor	/	12.	Conveyor belt	Carries the material.
2.	Scraper	Pulls the material.	13.	Drive pulley	Drives the belt.
3.	Conveyor chain	Scrapers are connected to the chain.	14.	Bevel gearbox	Transfers drive to the belt conveyor.
4.	Ball bearing set	Used for mounting.	15.	Roller conveyor	/
5.	Apron (slat) conveyor	/	16.	Roller	Carries the material.
6.	Apron (slat) of the conveyor	Carries the material.	17.	Gearbox 2:1	Transfers the drive from the planetary small geared motor to all conveyors.
7.	Cylindrical gears	Transfers drive to the apron (slat) conveyor.	18.	Gearbox 1:1	Transfers the drive to the apron (slat) conveyor and to the belt conveyor.
8.	First timing belt set	Transfers drive to the apron (slat) conveyor.	19.	Planetary small geared motor	Drives all conveyors.
9.	Second timing belt set	Transfers drive to the apron (slat) conveyor.	20.	Conical gears	Transfers the drive from the motor to the gearbox 2:1
10.	Tensioning pulley	Tensions the timing belt.	21.	Chain drive	Transfers the drive to the conical gearbox.
11.	Belt conveyor	/			

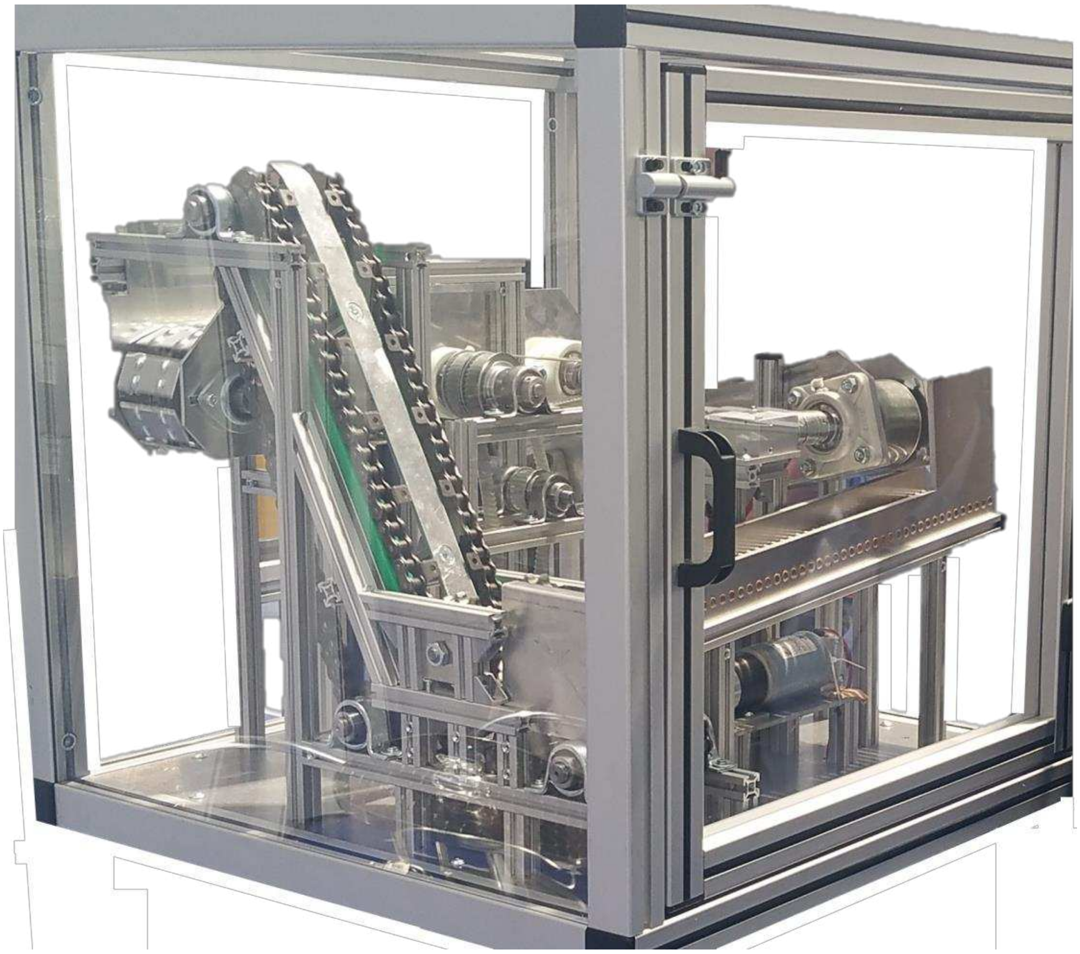

Fig. 3. Physical model of the transport system

2.1. Elements of the drive mechanism and supporting structure

The transport system is driven by a planetary small geared DC motor with maximum admissible permanent torque of 6 Nm, maximum starting torque of 16 Nm and nominal power of 32 W, 24 V and output speed 51 rpm, fig 4.

Fig. 4. Planetary small geared DC motor

The drive is transferred by conical gears to the first gearbox with the transmission ratio of 2:1, fig 5.

Fig. 5. Bevel gearbox

From the first gearbox the drive is transferred to the flight (scraper) conveyor on one side and to the second gearbox with the transmission ratio of 1:1 on the other side. From the second gearbox, the drive is divided in two ways. On one side of the second gearbox, the drive is transferred via chain drive to the angular bevel gearbox with the transmission ratio of 1:1, fig 6.

Fig. 6. Angular bevel gearbox

From the angular bevel gearbox, the drive is transferred to the belt conveyor via a self-aligning coupling, fig. 7.

Fig. 7. Self-aligning coupling

On the other side of the second gearbox, the drive is transferred via a pair of cylindrical gears and two timing belt sets to the apron (slat) conveyor.

Flight (scraper) conveyor, apron (slat) conveyor and belt conveyor are driven conveyors, while the fourth roller conveyor is without a drive and it is placed at an angle so it can ensure the movement of the material by gravity.

The complete transport system is conceptualized like an endless transport circle where a little box with dimensions 20x20x20 mm and mass of 0,0628 kg is continuously transported.

All elements are placed on aluminum profiles 20x20 mm with a special cross section which ensures proper rigidity of the support structure and simple assembling with bolted connections, fig. 8.

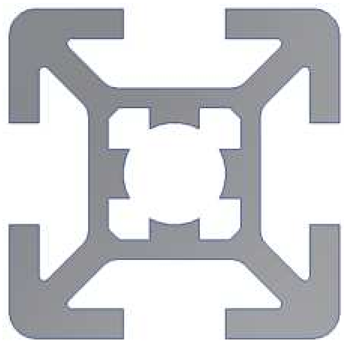

Fig. 8. Cross section of the aluminum support structure

2.2. Characteristics of the drive of conveyors

The input speed of the flight (scraper) conveyor shaft is 25,5 rpm which provides the linear speed of 0,088 m/s. The input speed of the apron (slat) conveyor shaft is 25,5 rpm which provides the linear speed of 0,1 m/s. The input speed of the belt conveyor shaft is 21,25 rpm which provides the linear speed of 0,088 m/s. The roller conveyor is placed at an angle of 5° and, due to the gravity, the transported box can achieve the speed of 0,766 m/s in ideal conditions at the end of the conveyor. Because of that, a metal bumper is positioned in front of the flight (scraper) conveyor loading point so the transported box cannot leave the endless transport circle.

The required drive powers of driven conveyors required for full transport capacities and transmission efficiencies of drive mechanisms which transfer the drive to them are:

- flight (scraper) conveyor – 21 W and 94%;
- apron (slat) conveyor – 23,4 W and 86,7%;
- belt conveyor – 10 W and 84,1%.

The total required power for full transport capacity of three driven conveyors is 61,2 W which is greater than the power of the planetary small geared DC motor 32 W. Concerning that the transport system operates only with one box, the rated power of the chosen drive motor is more than enough which was proved when the physical model was completed and tested.

2.3. Characteristics of conveyors

As mentioned before, the transport system is consisted of four conveyors – flight (scraper) conveyor, apron (slat) conveyor, belt conveyor and roller conveyor. First three are driven and the fourth is without a drive, it uses gravity for material transport.

The first conveyor is the flight (scraper) conveyor which 3D model is shown in fig 9. and the physical model is shown in fig. 10.

Fig. 9. 3D model of the flight conveyor

Fig. 10. Physical model of the flight conveyor

It has two roller chains, four sprocket sets from which one set is the driven set and one set is the tension set. The pitch of the chains is 15,875 mm, the diameter of sprockets is 66,32 mm and the pitch of scrapers is 63,5 mm. The transport speed is 0,088 m/s.

The second conveyor is the apron (slat) conveyor which 3D model is shown in fig. 11. and the physical model is shown in fig 12.

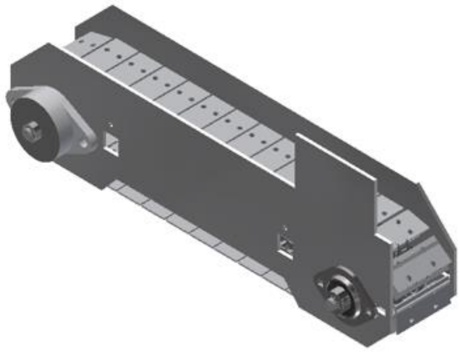

Fig. 11. 3D model of the apron conveyor

Fig. 12. Physical model of the apron conveyor

It has one roller chain, two sprocket sets from which one set is the driven set and the other set is the tension set. The pitch of the chains is 15,875 mm, the diameter of sprockets is 76,36 mm. The transport speed is 0,1 m/s.

The third conveyor is the belt conveyor which 3D model is shown in fig. 13. and the physical model is shown in fig 14.

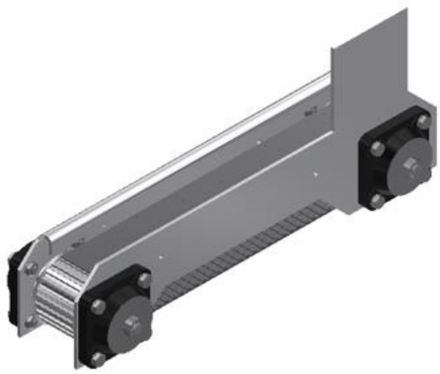

Fig. 13. 3D model of the belt conveyor

Fig. 14. Physical model of the belt conveyor

It has one belt with the width of 50 mm, it has two pulleys with the diameter of 79,58 mm from which one is the driven pulley and the other is the tension pulley. The transport speed is 0,88 m/s.
The fourth conveyor is the roller conveyor which 3D model is shown in fig. 15. and the physical model is shown in fig 16.

Fig. 15. 3D model of the roller conveyor

Fig. 16. Physical model of the roller conveyor

It has 38 rollers with the diameter of 8 mm. It is placed at an angle of 5°. The maximum transport speed that can be achieved by the transported box in ideal conditions is 0,766 m/s.

3. CONCLUSION

The physical model is important for students of mechanical engineering in the field of Mechanization and Design Engineering within the Faculty of Technical Sciences Novi Sad, because they can see a large number of standard mechanical elements, which are studied during their studies and which are installed on conveyors.
Also, students on the formed physical models can see the functionality of these conveyors, notice the basic elements of the conveyor, realize their advantages and disadvantages.
In this way, students acquire valuable practical knowledge that will to some extent correct their future design solutions in terms of considering a number of influencing aspects.

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REFERENCES

[1] Goodchild, S., Sriraman, B.: Revisiting the didactic triangle: from the particular to the general. *ZDM – Mathematics Education*, Vol. 44, pp. 581-585, ISSN: 1863-9690, 2012
[2] Geiger, V.: Strasser's Didactic Tetrahedron as a basis for theorizing mathematical modelling activity within social contexts, In: *Teaching mathematical modelling: connecting to research and practice*, Stillman, G., Kaiser, G., Blum, W., Brown J., pp. 107-116, Springer, Dordrecht, ISBN: 97894007654-05, 2013
[3] https://www.maedler.de – Company Mädler, Accessed on 2022-05-02
[4] https://www.maytec.com.de – Company MayTec, Accessed on 2022-05-02

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OPTIMIZATION OF WELDED BEAM DESIGN PROBLEM USING HONEY BADGER ALGORITHM

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Miroslav VULIĆ
Željko STOJANOVIĆ
Ivan PALINKAŠ

Abstract: *A recently proposed metaheuristic algorithm named Honey badger algorithm (HBA in short) is adopted in this study to find optimal fabrication cost of the welded beam design. Firstly, the inspiration behind the HBA algorithm is briefly described and concept of the algorithm is presented in pseudocode. Next, the welded beam design optimization problem is defined and the mathematical model is presented in detail. The comparative study is performed and the performances of HBA are compared with performances of different traditional, as well as novel metaheuristic algorithms. Minimal, maximal, mean fitness value and standard deviation are used as performance metrics to evaluate the efficiency of HBA. Finally, convergence graphs are compared to conclude the study.*

Keywords: *welded beam design; optimization; honey badger algorithm*

1. INTRODUCTION

In the last few decades, a significant amount of attention has been given to the field of optimization. Optimization can be defined as a numerical process used to determine design variables for the purpose of minimizing or maximizing an objective function while complying with linear or nonlinear constraints which can be equalities and/or inequalities [1]. Numerous real-world optimization problems defined by nonlinear objective functions and constraints contain a large number of local optima which makes them complex to solve. These problems are popularly defined in the literature as constrained optimization problems. To solve a constrained optimization problem successfully, the goal is not only to minimize/maximize the predefined objective function/functions, but also to satisfy all design constraints [2]. So far, different mathematical optimization techniques have been proposed in order to tackle the constrained optimization problems [3]. One of main limitations lies in the fact that they require derivative information and their deterministic nature often leads to local optima entrapment. These reasons raised interest in derivative-free optimization techniques with stochastic nature which lead to development of metaheuristic algorithms. Metaheuristics are randomization-based probabilistic algorithms that have proven their performance and reliability in finding optimal or near-optimal solutions to complex engineering problems. These algorithms can be classified into many categories depending on the source of their inspiration [4]. Many intelligent principles from biology, physics, society, or simply, from nature have been adopted to develop optimization algorithms. Some of the most popular categories are evolutionary algorithms, such as genetic algorithm or differential evolution, and swarm intelligence based algorithms, such as particle swarm optimization or grey wolf optimizer. In this paper, a recently proposed swarm intelligence algorithm named Honey Badger Algorithm (HBA) is adopted to solve the popular welded beam design problem as an example of a constrained optimization problem. After defining the inspiration and the concept behind HBA technique, the welded beam design problem is presented in detail. Full description and mathematical formulation of design variables, objective function, design constraints and bounds is presented and schematic view of the welded beam is given. Afterwards, computational results are shown in tables and convergence graphs. Comparative study is conducted in order to compare performances of HBA with performances of different metaheuristic algorithms, such as GA, PSO, GWO, BA and others. The results are discussed and conclusions are made. Lastly, the adopted references are listed in the last chapter.

2. HONEY BADGER ALGORITHM

Honey badger algorithm (HBA) is a novel population-based optimization algorithm proposed by [5] in 2022. It is inspired by foraging behavior of honey badgers. Honey badgers are primarily carnivore predators with a wide diet range (Fig. 1). They are recognized by its ferocious nature. If attacked, these brave creatures become very aggressive even towards much larger predators. Very good smelling skills help them locate small animals (larvae, rodents, lizzards, insects) and by digging holes using their long claws, they find and catch their prey. Honey badgers fancy a wild honey, by which they got the name. To locate behive and enjoy its honey, a honey badger gets aid from a bird called honeyguide. This interesting connection between two animals leads honey badger to the food source after which they both enjoy the reward [6,7].

Fig. 1. Honey badger [8]

The concept of HBA is based on two different strategies honey badgers use when finding food. In "digging phase", a honey badger use smelling abilities to locate the prey, then start moving around and choosing place to dig hole until finally catch it. The second case is "honey phase", in which a honey badger follows a honeyguide bird to help it reach a beehive.
Mathematical formulation of HBA consists of several steps and, here, the main components will be emphasized. In initial phase, after setting input parameters of HBA, the population of feasible honey badger positions is generated and fitness of each of these positions is evaluated. The result of the initial phase should be the position of the prey, x_{prey}, as the best individual in the population of honey badger positions, and the best fitness value which represents fitness of the prey, f_{prey}.
To engage in the "digging phase" or the "honey phase", some important elements of the search have to be considered. First, intensity, I_i, which represents the smell intensity of the prey and depends on the concentration strength of the prey S and the distance between the prey and the i_{th} honey badger, d_i. According to these values, intensity can be formulated using the Inverse square law equation:

$$I_i = rand_1 \cdot \frac{S}{4\pi d_i^2} \quad (1)$$

Fig. 2a illustrates a honey badger motion that is based on Inverse square law. High intensity of the smell makes honey badger move faster, and vice versa. Concentration strength of the prey S, and distance d_i, can be defined by equations (2) and (3):

$$S = (x_i - x_{i+1})^2 \quad (2)$$

$$d_i = x_{prey} - x_i \quad (3)$$

A parameter that affects transition from global to local search is the density factor α which is formulated using equation:

$$\alpha = C \cdot e^{\left(\frac{-it}{it_{max}}\right)} \quad (4)$$

The flag F which represents disturbance a honey badger may find on the way to the prey, can be defined using the following condition:

$$F = \begin{cases} 1 & \text{if rand}_2 \le 0.5 \\ -1 & \text{else} \end{cases} \quad (5)$$

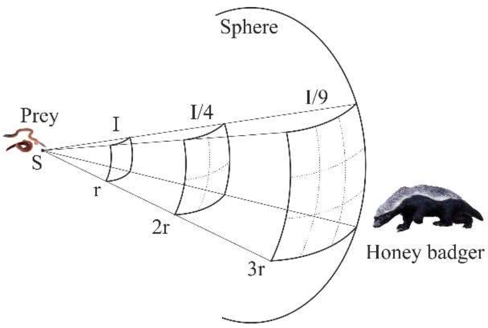
Honey badger gets into a digging mode performing Cardioid motion which is illustrated in Fig.2b. Accordingly, a honey badger and updates its position using equation (6):

$$x_{new} = x_{prey} + F \cdot \beta \cdot I_i \cdot x_{prey} + F \cdot \text{rand}_3 \cdot \alpha \cdot d_i \cdot |\cos(2\pi \text{rand}_4) \cdot [1 - \cos(2\pi \text{rand}_5)]| \quad (6)$$

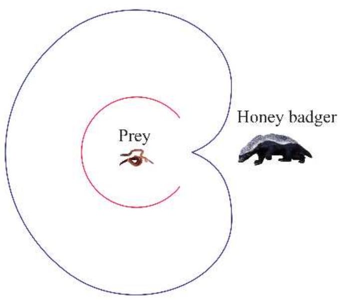
On the other side, honeyguide helps honey badger update its position to find a beehive (Fig.2c) which is formulated with this equation:

$$x_{new} = x_{prey} + F \cdot \text{rand}_6 \cdot \alpha \cdot d_i \quad (7)$$

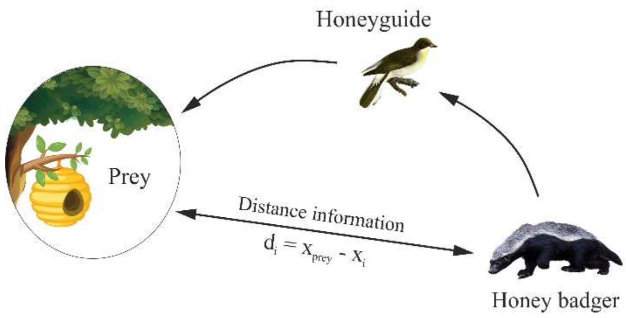
In the aforementioned equations, $rand_1$ to $rand_6$ are random numbers from interval [0,1] and it and it_{max} are current iteration of HBA, and the maximum number of iterations. x_i and x_{i+1} are positions of a honey badger in current iteration and the next iteration of HBA, while x_{new} is the updated position according to equations (6) and (7). Pseudocode of HBA is given in Table 1.



a) Motion based on Inverse square law



b) Cardioid motion – Digging phase



c) Honey phase

Fig. 2. Main phases of HBA

Table 1. Pseudo code of HBA [5]

Initial phase:
Setting HBA parameters: it_{max}, N, β and C.
Initializing population of honey badgers with random positions.
Evaluating fitness f_i of each honey badger position x_i
Store best position as position of the prey, x_{prey} , and best fitness as fitness of the prey, f_{prey} .
Main loop:
for it = 1 to it_{max}
    Update the decreasing factor α using equation (4)
    for i = 1 to N
        Calculate smell intensity of the prey, I_i, using equations (1-3)
        if r < 0.5
            % Digging phase / Cardioid motion
            Update the new position of the badger, x_{new}, using equation (6)
        else
            % Honey phase
            Update the new position of the badger, xnew, using equation (7)
        end if
        Evaluate new position of the badger, f_{new}.
        if $f_{new} \leq f_i$
            $x_i = x_{new}$
            $f_i = f_{new}$
        end if
        if $f_{new} \leq f_{prey}$
            $x_{prey} = x_{new}$
            $f_{prey} = f_{new}$
        end if
    end for
end for %After reaching maximum number of iterations
Output results: x_{prey}, f_{prey}

3. WELDED BEAM DESIGN PROBLEM – MATHEMATICAL MODEL AND OPTIMIZATION RESULTS

The goal of this constrained optimization problem is to minimize the fabrication cost of a welded beam. Its 3D and 2D illustration is shown in Fig. 3 in. One of the first mentions of the welded beam design problem can be found in [9]. A rectangular beam is welded to a rigid support as a cantilever beam in order to carry a constant load F without failure [10].

The welded beam shown in Fig. 3 is subject to several optimization constraints, such as shear stress (τ), bending stress in the beam (σ), buckling load (F_c) and beam deflection (δ). Also, four design variables are taken into account: thickness of weld (h), length of the attached part of the bar (l), height of the bar (t) and the thickness of the bar (b). Assuming that the beam is used to support the constant load of F (26.7 kN) at the fixed length L (355.6 mm), the mathematical model can be obtained [11]:

Design variables:

$$x = \{h, l, t, b\} \tag{8}$$

Objective function:

$$Minimize: f(x) = 1.10471 \cdot h^2 \cdot l + 0.04811 \cdot t \cdot b \cdot (14.0 + l) \tag{9}$$

Subject to:

Design constraints (inequalities):

$$g_1(x) = \tau(x) - \tau_{max} \leq 0 \tag{10}$$

$$g_2(x) = \sigma(x) - \sigma_{max} \leq 0 \tag{11}$$

$$g_3(x) = h - b \leq 0 \tag{12}$$

$$g_4(x) = 0.1047 \cdot h^2 + 0.04811 \cdot t \cdot b \cdot (14.0 + l) - 5 \leq 0 \tag{13}$$

$$g_5(x) = 0{,}125 - h \leq 0 \tag{14}$$

$$g_6(x) = \delta(x) - \delta_{max} \leq 0 \tag{15}$$

$$g_7(x) = F - F_c(x) \leq 0 \tag{16}$$

where:

$$\tau = \sqrt{(\tau')^2 + (\tau'')^2 + 2\tau'\tau''\frac{l}{2R}}, \tag{17}$$

$$\tau' = \frac{F}{\sqrt{2}hl} \tag{18}$$

$$\tau'' = \frac{MR}{J}, \quad M = F\left(L + \frac{l}{2}\right) \tag{19}$$

$$R = \sqrt{\frac{l^2}{4} + \frac{(h+t)^2}{4}} \quad (20)$$

$$J = 2\left\{\sqrt{2}hl\left[\frac{l^2}{12} + \frac{(h+t)^2}{4}\right]\right\} \quad (21)$$

$$\sigma = \frac{6FL}{b\,t^2} \quad (22)$$

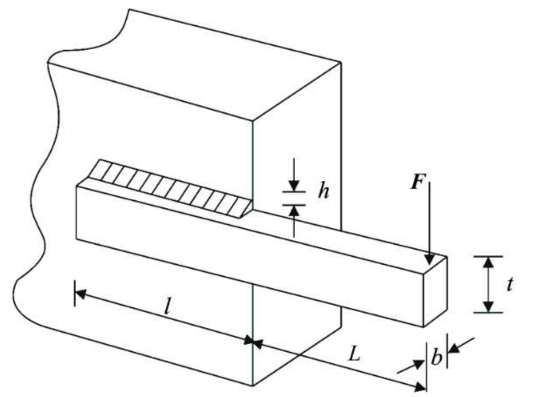
$$F_c = \frac{4.013E\sqrt{t^2 b^6/36}}{b\,t^2}\left(1 - \frac{t}{2L}\sqrt{\frac{E}{4G}}\right) \quad (23)$$

and *bounds*:

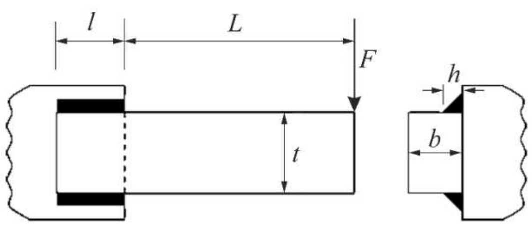
$$0.1\ in\ (2.54\ mm) \le h, b \le 2\ in\ (50.8\ mm) \quad (24)$$

$$0.1\ in\ (2.54\ mm) \le l, t \le 10\ in\ (254\ mm) \quad (25)$$

Regarding equations (17-23), the following values are given: applied tip load, F = 6000 lb (26.7 kN), length of cantilever part of beam, L = 14 in (355.6 mm), Young's modulus of beam, E = $30 \cdot 10^6$ psi (206.84 GPa), shear modulus of beam, G = $12 \cdot 10^6$ psi (82.74 GPa), maximum allowed shear stress, τ_{max} = 13600 psi (93.77 MPa), maximum allowed bending stress, σ_{max} = 30000 psi (206.84 MPa), and maximum allowed tip deflection, δ_{max} = 0.25 in (6.35 mm).
To successfully perform comparative analysis, British engineering units have to be considered since the mathematical model of welded beam design is developed in accordance with this system of measurement. However, after comparing results of HBA with competing metaheuristic algorithms, optimal design solutions (*h*, *l*, *b* and *t*) will be given in SI units as well.



a) 3-dimensional schematic view[12]



b) 2-dimensional schematic view[10]

Fig. 3. The welded beam design problem

4. COMPUTATIONAL RESULTS

In the current study, the performances of the HBA are measured using statistical values, mean, worst and best fitness values. Also, standard deviation of results achieved in 50 independent runs is used to check the consistency of several metaheuristic algorithms that have been adopted in this comparative study. These algorithms are: Particle swarm optimization (PSO), Whale Optimization Algorithm (WOA), Grey Wolf Optimizer (GWO), Genetic Algorithm (GA), Crow Search Algorithm (CSA), Bat Algorithm (BA), Artificial Bee Colony (ABC), and Seagull Optimization Algorithm (SOA). All algorithms are coded in Matlab R2016b on the laptop computer with Intel i7 1.9 GHz processor, 8 GB of RAM and Windows 10 operating system. Before comparing performances, a brief sensitivity analysis of HBA parameters is performed in order to obtain the most suitable set of input parameters. According to [5], two user-defined parameters, β and C, are the main two values that affect the performances of classical HBA and therefore, require a certain amount of attention. As shown in Table 2, several scenarios are considered, and the statistical values are obtained. By taking into account the welded beam design problem, the most suitable values for β are 2 and 4 while best value for constant C is 2. Slightly better deviation of results (0,0000048866) is achieved when β equals 4, so that combination of input values is adopted here, β=4 and C=2. The obtained results and performance metrics for nine different metaheuristics on welded beam design problem are presented in Table 3. Mean fitness values consider the mean fitness obtained in 50 independent runs. The population of search agents in each metaheuristic is set to 50 and maximum number of iterations of each metaheuristic is set to 1000. According to Table 3, HBA, after finding optimal parameter settings, found the optimal fabrication cost in almost each run of the algorithm. With additional parameter tuning, other metaheuristics in this comparative analysis, could perform better and possibly achieve more consistent results. The results prove the efficiency of HBA for solving the considered constrained optimization problem.
The best solutions that are found are included in Table 4. The resulting values achieved by all metaheuristic algorithms are given in inches according to British system of units. Regarding the results of HBA, the optimal design solutions are also given according to the International System of Units: thickness of weld h = 5.225542 mm (0.20573 in), length of the attached part of the bar l = 88.1507 mm (3.4705 in), height of the bar t = 229.52964 mm (9.0366 in) and the thickness of the bar b = 5.225542 mm (0.20573 in). Cost units for fitness values are not specified in the mathematical model.

Table 2. Sensitivity analysis for HBA parameters β and C

Performance measures	HBA parameter scenarios					
	β = 6, C = 0.5	β = 4, C = 0.5	β = 2, C = 0.5	β = 2, C = 2	**β = 4, C = 2**	β = 6, C = 2
Mean fitness	2,0975	2,0145	2,1098	1,7249	**1,7249**	1,7249
Worst fitness	3,2142	3,7632	4,1094	1,7249	**1,7249**	1,7251
Best fitness	1,7249	1,7249	1,7249	1,7249	**1,7249**	1,7249
St. deviation	0,45187	0,4319	0,49883	0,000012615	**0,0000048866**	0,000032011

Table 3. Comparison of statistical values by the applied metaheuristic algorithms on the welded beam design problem

Performance measures	Metaheuristic algorithms								
	PSO	WOA	SOA	GWO	GA	CSA	BA	ABC	**HBA**
Mean fitness	1,7622	2,2642	1,7387	1,7266	6,0459	2,3352	2,8375	2,1465	**1,7249**
Worst fitness	2,2192	4,4519	1,7710	1,7302	15,4655	2,7603	4,0624	2,4092	**1,7249**
Best fitness	1,7249	1,7676	1,7290	1,7252	2,5913	1,8983	1,8187	1,8705	**1,7249**
St. deviation	0,0895	0,63765	0,0076	0,00107	2,48285	0,2064	0,5651	0,1193	**4.8e-06**

Table 4. Best solutions obtained by the applied metaheuristic algorithms on the welded beam design problem

Design variables	Metaheuristic algorithms								
	PSO	WOA	SOA	GWO	GA	CSA	BA	ABC	**HBA**
h	0,2057	0,1990	0,2066	0,2057	0,27139	0,1903	0,1747	0,1821	**0,20573**
l	3,4705	3,8321	3,4602	3,4718	6,7579	3,8282	4,0815	3,9512	**3,4705**
t	9,0366	9,0083	9,0259	9,0368	8,3914	9,5648	9,4934	9,6505	**9,0366**
b	0,2057	0,2070	0,2070	0,2058	0,2436	0,2127	0,2036	0,2071	**0,20573**
f_{best}	1,7249	1,7676	1,7290	1,7252	2,5913	1,8983	1,8187	1,8705	**1,7249**

Convergence graph comparison for the considered metaheuristics is demonstrated in Fig. 4 for one independent run. Assuming the stochastic nature of metaheuristics, it is expected that each run provides slight difference in convergence meaning that consistency is hardly obtained. It can be seen that HBA, depicted in black colored line, converges towards the global optimum in the early stages of the search process, similarly to PSO and GWO algorithms.

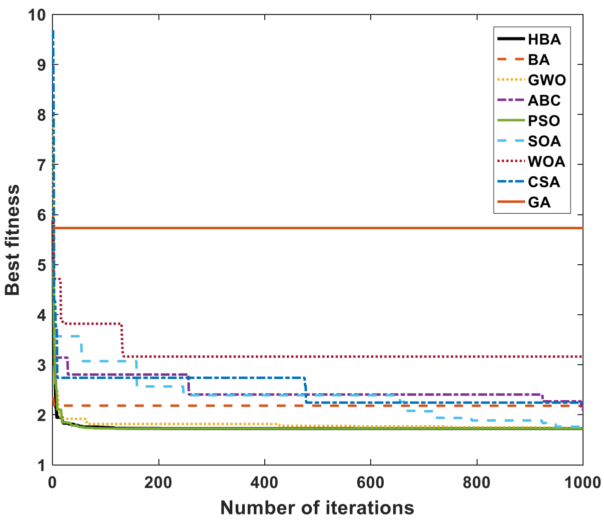


Fig 4. Convergence graph of applied metaheuristics in the comparative study

This demonstrates that HBA managed to avoid local optima very early and reach the best possible result. GWO also shows very good performances, while SOA achieves good results, but with very slow convergence. Other algorithms require additional parameter tuning and/or modifications in order to improve their convergence and efficiency.

5. CONCLUSION

Honey badger algorithm (HBA) was proposed in this paper to find the optimal fabrication cost of welded beam design which is one example of constrained optimization problems. To do so, after brief introduction to constrained optimization and metaheuristic algorithms, the biological background and mathematical model of HBA are given. Also, the pseudo code of this algorithm is presented to show the main steps of this optimization technique. Afterwards, welded beam design problem is presented graphically as well as in a mathematical form including objective function, constraints and bounds. Then, the results of the comparative study are presented. HBA is compared against several metaheuristic algorithms and the performances showed the consistency of the obtained results and proved the efficiency of HBA. Finally, convergence graphs of the adopted algorithms were also compared where HBA showed abilities to avoid local optima and move search process towards global optimum.

REFERENCES

[1] Kumar, A., Wu, G., Ali, M.Z., Mallipeddi, R., Suganthan, P.N., Das, S.: A test-suite of non-convex constrained optimization problems from the real-world and some baseline results, Swarm and Evolutionary Computation, Vol. 56, 100693, ISSN 2210-6502, 2020.

[2] Mezura-Montes, E., Coello Coello, C.A.: Constraint-handling in nature-inspired numerical optimization: Past, present and future, Swarm and Evolutionary Computation, Vol. 1, No. 4, pp. 173-194, ISSN 2210-6502, 2011.

[3] Mirjalili, S., Dong, J. S., Lewis, A.: Nature-inspired optimizers: theories, literature reviews and applications. Springer, Switzerland, ISBN 978-3-030-12126-6, 2019.

[4] Đurđev, M.: Application of novel metaheuristic algorithms in optimization of process planning, PhD thesis (in Serbian), University of Novi Sad, Faculty of Technical Sciences, Novi Sad, 2021.

[5] Hashim, F. A., Houssein, E. H., Hussain, K., Mabrouk, M. S., Al-Atabany, W.: Honey Badger Algorithm: New metaheuristic algorithm for solving optimization problems, Mathematics and Computers in Simulation, Vol. 192, pp. 84-110, ISSN 0378-4754, 2022.

[6] Internet source: http://www.honeybadger.com/diet.html

[7] Internet source:

[8] https://pediaa.com/difference-between-badger-and-honey-badger

[9] Internet source:

[10] https://en.wikipedia.org/wiki/Honey_badger

[11] Coello Coello C. A.: Use of a self-adaptive penalty approach for engineering optimization problems, Computers in Industry, Vol. 41, No. 2, pp. 113-127, ISSN 0166-3615, 2000.

[12] Data, D., Figueira, J. R.: A real-integer-discrete-coded particle swarm optimization for design problems, Applied Soft Computing, Vol. 11, No. 4, pp. 3625-3633, ISSN 1568-4946, 2011.

[13] Gupta, S., Abderazek, H., Yildiz, B. S., Yildiz, A. R., Mirjalili, S., Sait, S. M.: Comparison of metaheuristic optimization algorithms for solving constrained mechanical design optimization problems, Expert Systems with Applications, Vol. 183, 115351, ISSN 0957-4174, 2021.

[14] Kaur, A., Jain, S., Goel, S.: Sandpiper optimization algorithm: a novel approach for solving real-life engineering problems. Applied Intelligence, Vol. 50, pp. 582–619, ISSN 1573-7497,2020.

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INVESTIGATION OF THE INFLUENCE OF LATTICE STRUCTURES ON PRODUCT ' S MECHANICAL PROPERTIES

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Davorka ŠARAVANJA
Adisa VUČINA
Nebojša RAŠOVIĆ

Abstract: *Compared to conventional manufacturing processes, additive manufacturing enables impressive progress in the fabrication and design of cellular materials, including complex lattice structures. That is why lightweight products have received much more attention and significance in their application over the last decade. Various additive techniques allow designers to modify cellular materials and lattice structures to enhance the product's performance, especially its mechanical characteristics. The mechanical behaviour of these structures is being considered through the product stress state, which influences getting their optimal shapes. Thus, the structures are intensively studied due to superior mechanical properties and applications in various fields. The paper provides an overview of the literature and presents an overarching analysis of lattice structure application.*

Keywords: *lattice structures; additive manufacturing; topology optimisation*

1. INTRODUCTION

Inspired by nature, cellular materials such as grapefruit peel, bamboo, turtle shell and bone are known for their high specific strength [1]. This structure is composed of a matrix with many pores, and they are called porous structures. That is the reason why human-made cellular materials have been investigated. In recent years, additive manufacturing techniques have been increasingly used due to the possibility of advanced fabricating of complex geometries [2]. Among them, especially lattice structures are introduced.

Lattice structures are defined as interconnected struts and nodes creating three-dimensional structures by repeating unit cells [3]. By researching this topic, it is concluded that lattice structures have received more attention than other cellular structures due to their superior properties. In the medical field, it is possible to produce orthopaedic implants whose stiffness is almost close to the stiffness of bone [4]. Lattice structures are lightweight products that replace solid parts in aircraft to reduce the weight of the parts. Also, these structures are widely used in various fields like mechanical engineering and the automotive industry [5].

Given the excellent properties such as low density, high strength, stiffness and strength-to-weight ratio, the lattice structures provide vast possibilities and allow progress in further research.

2. RELATED WORKS

Lattice structures improve additive manufacturing processes by reducing costs and fabrication time [6]. Newly designed structures are tested in order to improve their mechanical properties. Thus, Alomar et al. manufactured a circular cell-based lattice structure via a selective laser melting process with three wall thicknesses which showed better load-bearing capacity and stiffness than the BCC structure under static load [7]. The topology optimisation should consider the diameter of the strut and cell size [8]. If the number of unit cells is too high, the lattice generation time increases exponentially [9]. Luo et al. presented mechanical models describing stress-strain curves and their mechanical behaviour during compression or tensile [10]. The number of unit cells affects the strength [6] but adding fillets improves the stiffness [11]. Therefore, some results show that a sample consisting of a 3×3×3 cubic lattice structure is selected as the most efficient pattern configuration. Park at el. has proven that this structure shows excellent compression parameters [12].

For this reason, this paper aims to review and compare several characteristic lattice structures and observe their behaviour under compressive loading characteristics intended for plastic materials. Then, it is necessary to determine the most suitable material for lattice structure with the best parameters.

3. METHOD OF LATTICE STRUCTURES DEFINITION

The algorithm for generating and analysing lattice structure is thoroughly presented (Fig. 2). A decision on which unit cell type is being observed represents the first step in this process. The literature review has derived five types of unit cells for analysis: Body Center with Struts, Kelvin, Octagonal, Rhombicuboctahedron and Simple Cubic (Fig. 1).

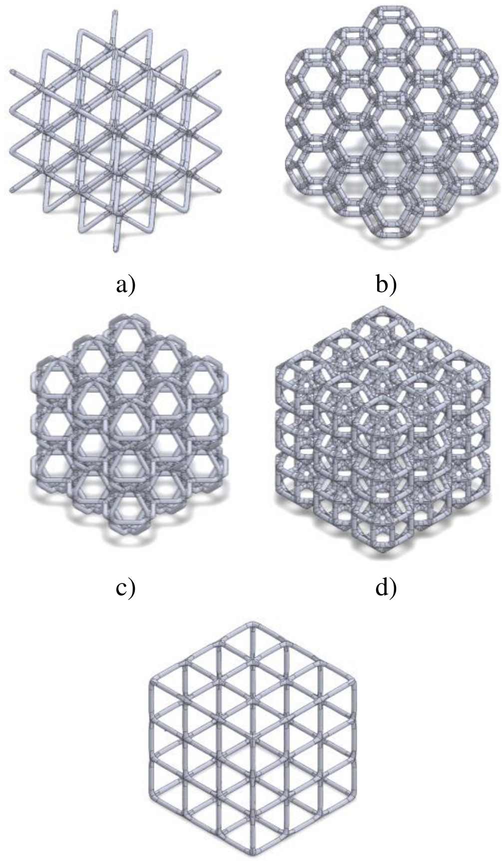

Fig.1. Five different types of lattice structures: a) Body Center with Struts; b) Kelvin; c) Octagonal; d) Rhombicuboctahedron and e) Simple Cubic

Rhino 7 has been used for generating those unit cells. The following steps in the algorithm include unit cell size definition, array pattern, and cell shape control parameters. The unit cell size is 10×10×10 mm in a rectangular array with a 3×3×3 pattern on the x, y, and z-axis. The circular cross-section is selected to control cell shape with a 0.5 mm defined radius. Previously mentioned research [12] gave the best results on compression test for array pattern of 3×3×3 with unit cell dimensions of 10×10×10 mm opposite to patterns: 1×1×1, 2×2×2 and 4×4×4. This fact serves as a reference starting point for deriving the research results.

Rhino 7 allows smooth control in generating models, and in order to reduce the simulation time, it is adopted to use a lower model smooth value of 0.5. After that, the bottom and top square surfaces are necessary for boundary conditions evaluation in static analysis.

An essential step for analysis is that those three features (top surface, bottom surface and lattice structure) must represent a single component using a Boolean operation unit (Solid – Union). The single-component arrangement ensures a reasonable time and facilitates analysis in general.

Analysis of five different lattice structures is fully-conducted in ANSYS Workbench, where Polylactic Acid (PLA) material is chosen as the most-used plastic material in the 3D printing process. PLA material gives a great look to printable models, and it is easy to print and has lower impact strength. Prototyping specimens and experimental observations present future research activities.

The mesh is defined by the automatic default method as the initial point in FEA's model parametrisation. The bottom surface is used as fixed support geometry, while the top surface is used to apply 100 N compression force loading.

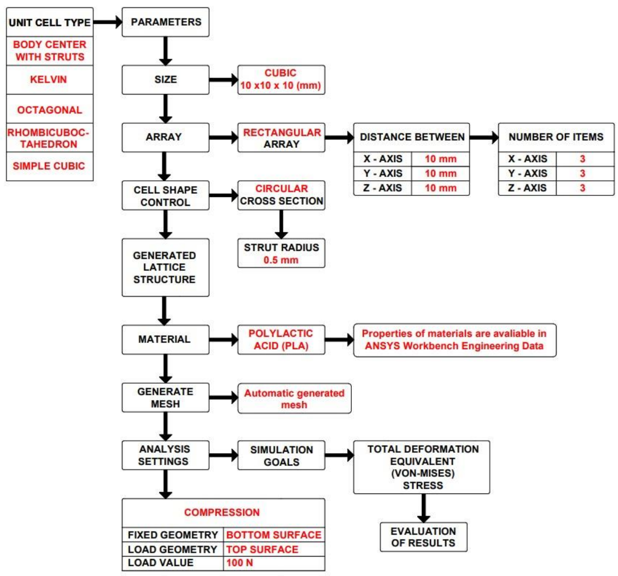

Fig.2. Algorithm of lattice structures analysis

4. RESULTS OF ANALYSIS

Two main simulation criteria are the point of interest: Total Deformation and Equivalent (von-Mises) Stress. These two criteria will show which structure has a suitable response under loading conditions adopted for plastic materials. In this paper, numerical solutions are limited to these two criteria, but the simulation of component working conditions will complement them in future research, including suitable lattice structure embodiment.

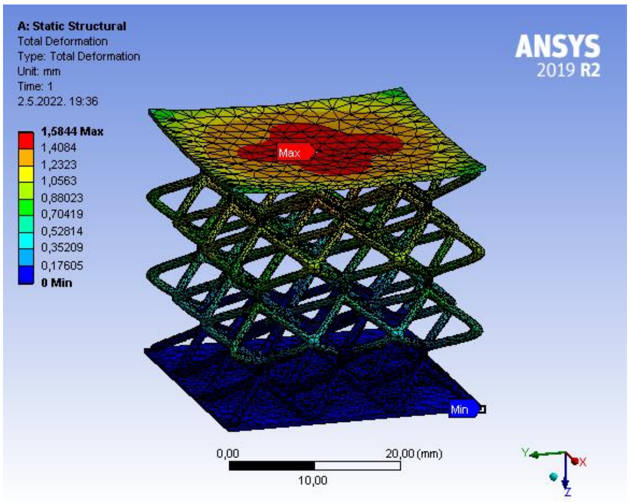

Fig.3. Distribution of Deformation on Body Center with Struts lattice structures

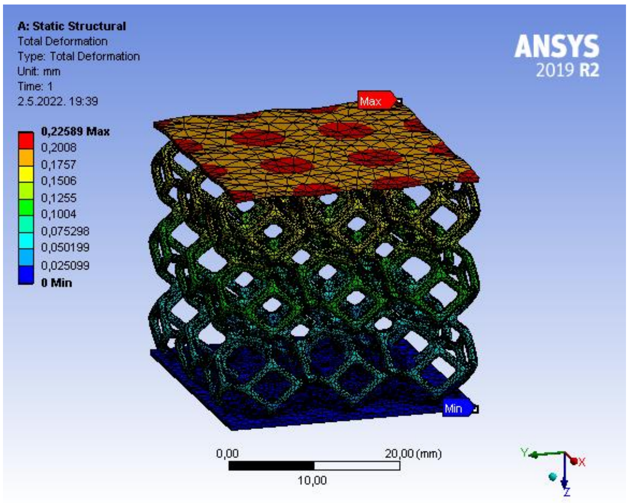

Fig.4. Distribution of Deformation on Kelvin lattice structures

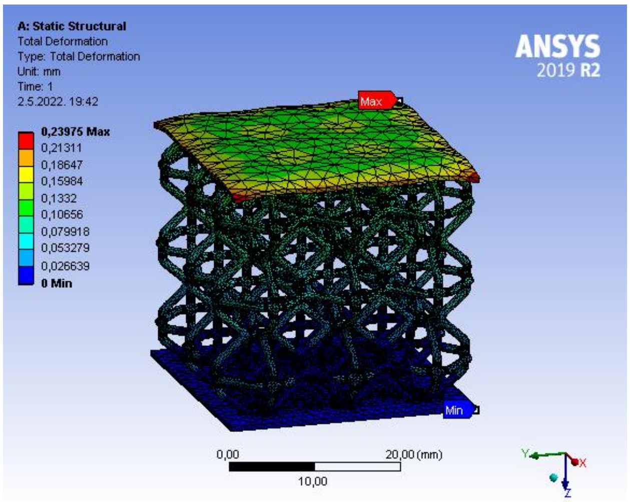

Fig.5. Distribution of Deformation on Octagonal lattice structures

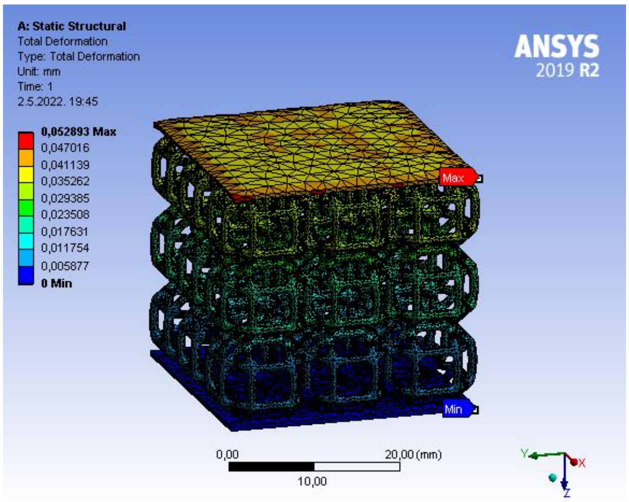

Fig.6. Distribution of Deformation on Rhombicuboctahedron lattice structures

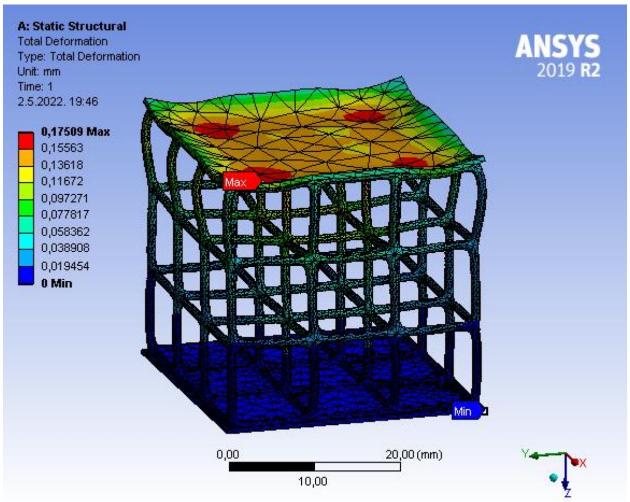

Fig.7. Distribution of Deformation on Simple Cubic lattice structures

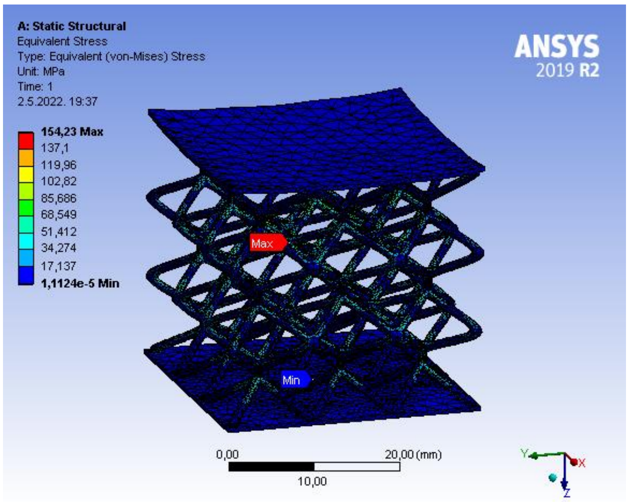

Fig.8. Distribution of Equivalent (von-Mises) Stress on Body Center with Struts lattice structures

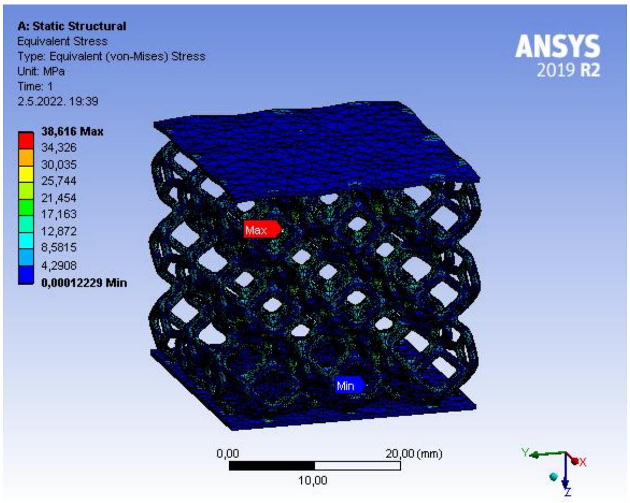

Fig.9. Distribution of Equivalent (von-Mises) Stress on Kelvin lattice structures

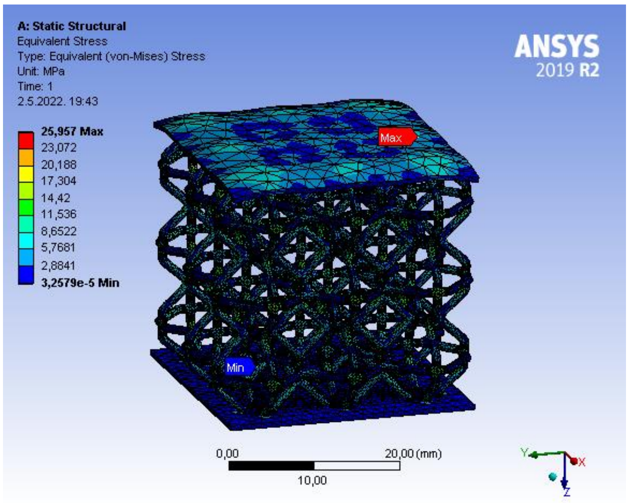

Fig.10. Distribution of Equivalent (von-Mises) Stress on Octagonal lattice structures

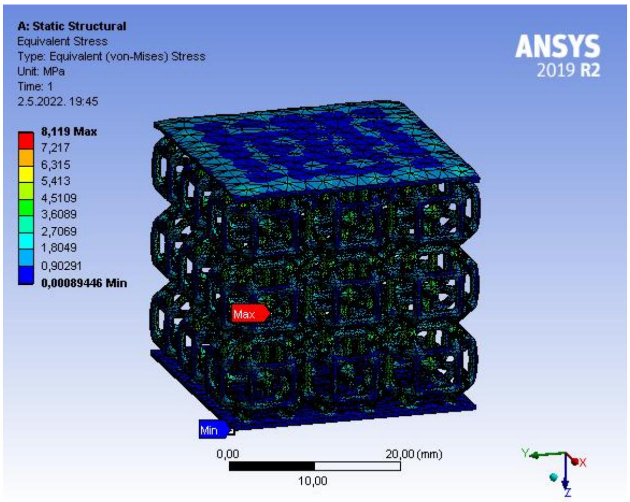

Fig.11. Distribution of Equivalent (von-Mises) Stress on Rhombicuboctahedron lattice structures

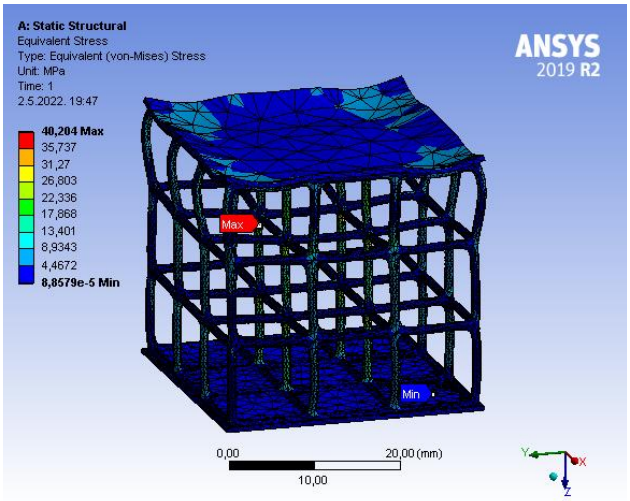

Fig.12. Distribution of Equivalent (von-Mises) Stress on Simple Cubic lattice structures

5. DISCUSSION

All results have been obtained from finite element analysis and summarised in Table 1.

Table 1. Results of Total Deformation and Equivalent (von-Mises) Stress for five different lattice structures

Type of lattice structures	**Total deformation (mm)**	**Equivalent stress (MPa)**
Body Center with Struts	1.5844	154.23
Kelvin	0.2259	38.616
Octagonal	0.2397	25.957
Rhombicub-octahedron	0.0529	8.119
Simple Cubic	0.1751	40.204

Rhombicuboctahedron lattice structure (with total deformation of 0.0529 mm under 100 N of compressive force) derived the smallest deformation value (Fig. 6.). Results show a minimal comparative deformation value and appear near the model's upper area. Results also show the smallest stress value (with Equivalent stress of 8.119 MPa) shown in Fig. 11. According to the results, the rhombicuboctahedron lattice structure has the most suitable stress and deformation distribution compared to other cases. This structure indicates the best loading response. The main reason for these good results could be the unit cell's topology formation due to the larger surface area in bond contact with the adjacent unit cells. In this case, unit cells have a significant withstand loading response.

The second result has achieved a Simple Cubic lattice structure (Fig. 7 and Fig. 12). Nevertheless, results disharmony is evident because the equivalent stress value is too high versus its deformation value. Considering the ratio of these two criteria values, the Octagonal has

derived better results than the Simple Cubic lattice structure (Fig. 5 and Fig. 10).
On the opposite side, Body Center with Struts shows the worst results with the highest criteria values (Fig. 3 and Fig. 8). The main reason for poor results is the weak unit cell surface contact (the intersection contact point of one cell with adjacent cells has weak contact due to insufficient cross-section size).
Kelvin (Fig. 4.) and Octagonal (Fig. 5.) lattice structures show a minimal difference where maximal deformation appears, including its values. They all have a stronger connection between unit cells. In all models, maximal equivalent stress is located near the top surface. Only Rhombicuboctahedron is in the model's middle area.
The selection of the most suitable material for additive fabrication is also a key factor for getting the best final properties for lattice structures. The five most frequent filaments have been analysed under the static structural analysis on the Rhombicuboctahedron lattice structures: PEEK, PLA (Polylactic Acid), PET, PS (Polystyrene) and ABS. After adding material and running the simulation with the same boundary conditions, the results are in Table 2.

Table 2. Results of Total Deformation and Equivalent (von-Mises) stress for five different materials for Rhombicuboctahedron lattice structures

Type of material	**Total deformation (mm)**	**Equivalent stress (MPa)**
PEEK	0.0472	8.1498
PLA	0.0529	8.1190
PET	0.0629	8.1161
PS	0.0667	8.1340
ABS	0.0760	8.1466

As table 2 shows, the most suitable material is PEEK taking into account deformation value. The equivalent stress criterion does not help in decision making considering stress nature and its narrow values difference.

6. CONCLUSION

Given the concluding remarks, it has been several dilemmas in getting actual results. The first dilemma was the radius of unit cell struts, which contributed to analysing models with different R values. After prelaminar analysis, the decision has been that R 0.5 suits the defined boundary conditions and facilitates the analysis. Note that a disproportionate ratio between unit cell size and struts radius exceeds running calculation time. Given the numerical results conducted by the ANSYS Workbench simulation, derives the following:

- The most suitable lattice structure exposed by the defined boundary conditions is Rhombicuboctahedron.
- The main reason for good deformation results for Rhombicuboctahedron lattice structure attributes to the unit cell geometry.
- The most suitable material covered by the paper for Rhombicuboctahedron lattice structure 3D printing is PEEK.

Future research is based on establishing a mathematical model to verify the results experimentally. Also, it will be considered the possibilities for lattice embodiment design inside the component working conditions. The material characterisation for the Rhombicuboctahedron lattice structure will additionally be considered.
The results will be analysed considering the strut's position and orientation harmonised by geometric rules and advantages—the focus shifts toward the inclined plane and angle consideration.
Since the designed unit cell (Fig. 13) has derived encouraging results, it can be assumed that the struts' redistribution additionally contributes to results refinement, emphasising their positions and geometry.

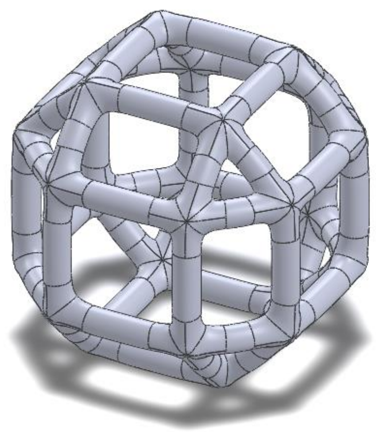

Fig.13. The unit cell of the Rhombicuboctahedron lattice structure

REFERENCES

[1] I. Echeta, X. Feng, B. Dutton, R. Leach, S. Piano, Review of defects in lattice structures manufactured by powder bed fusion, Int. J. Adv. Manuf. Technol. 106 (2020) 2649–2668. https://doi.org/10.1007/s00170-019-04753-4.
[2] N. Rašović, Recommended layer thickness to the powder-based additive manufacturing using multi-attribute decision support, Int. J. Comput. Integr. Manuf. 34 (2021) 455–469. https://doi.org/10.1080/0951192X.2021.1891574.
[3] C. Pan, Y. Han, J. Lu, Design and optimisation of lattice structures: A review, Appl. Sci. 10 (2020) 1–36. https://doi.org/10.3390/APP10186374.

[4] T. Maconachie, M. Leary, B. Lozanovski, X. Zhang, M. Qian, O. Faruque, M. Brandt, SLM lattice structures: Properties, performance, applications and challenges, Mater. Des. 183 (2019) 108137. https://doi.org/10.1016/j.matdes.2019.108137.

[5] A. Seharing, A.H. Azman, S. Abdullah, A review on integration of lightweight gradient lattice structures in additive manufacturing parts, Adv. Mech. Eng. 12 (2020) 1–21. https://doi.org/10.1177/1687814020916951.

[6] B.K. Nagesha, V. Dhinakaran, M. Varsha Shree, K.P. Manoj Kumar, D. Chalawadi, T. Sathish, Review on characterisation and impacts of the lattice structure in additive manufacturing, Mater. Today Proc. 21 (2020) 916–919. https://doi.org/10.1016/j.matpr.2019.08.158.

[7] Z. Alomar, F. Concli, Compressive behavior assessment of a newly developed circular cell-based lattice structure, Mater. Des. 205 (2021) 109716. https://doi.org/10.1016/j.matdes.2021.109716.

[8] S.O. Obadimu, K.I. Kourousis, Compressive behaviour of additively manufactured lattice structures: A review, Aerospace. 8 (2021). https://doi.org/10.3390/aerospace8080207.

[9] D.S. Nguyen, Design of lattice structure for additive manufacturing in CAD environment, J. Adv. Mech. Des. Syst. Manuf. 13 (2019) 1–12. https://doi.org/10.1299/jamdsm.2019jamdsm0057

[10] G. Luo, Y. Zhu, R. Zhang, P. Cao, Q. Liu, J. Zhang, Y. Sun, H. Yuan, W. Guo, Q. Shen, L. Zhang, A review on mechanical models for cellular media: Investigation on material characterisation and numerical simulation, Polymers (Basel). 13 (2021). https://doi.org/10.3390/polym13193283.

[11] A. Bin Arshad, A. Nazir, J.Y. Jeng, The effect of fillets and crossbars on mechanical properties of lattice structures fabricated using additive manufacturing, Int. J. Adv. Manuf. Technol. 111 (2020) 931–943. https://doi.org/10.1007/s00170-020-06034-x.

[12] K.M. Park, K.S. Min, Y.S. Roh, Design Optimization of Lattice Structures under Compression: Study of Unit Cell Types and Cell Arrangements, Materials (Basel). 15 (2022). https://doi.org/10.3390/ma15010097.

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MAPPING CONSTRAINED SEARCH IN TRUSS SHAPE OPTIMIZATION

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Abstract: *This paper presents a novel practical approach to shape optimization of simple truss structures. The 10 bar truss problem was considered in its topology optimized form which uses only 6 bars in order to decrease the number of variables to be mapped. An identification of eligible solutions was created according to the shape and all optimization iterations were mapped in order to define zones in which one or more constraints would be exceeded. Results indicate that deviation from node coordinates from the optimal, in the wrong direction, can result in surpassing constrained limits of displacement and/or buckling. The significance of these results is namely practically oriented and has the goal of defining potential and possible tolerances in truss construction and an analysis of the errors which could occur in assembly. This research creates a completely new approach to analyzing truss structures which can perspectival make construction easier in practice and prevent potential consequences as well as influence the decrease of costs of the overall truss.*

Keywords: *mapping; truss optimization; topology; shape; 10 bar truss*

1. INTRODUCTION

Searing technical development, an increasing use of computer aided engineering and strict industry standards in today's time have made optimization an integral part of every development process. Goals have always been to improve performance, efficiency, utilization while simultaneously saving on material, energy and other segments. These contradicting requests can be encompassed only by the use of optimization methods. For complex problems the use of computers in achieving this task is unavoidable. One of the robust, complex and difficult engineering problems is the design of truss structures. So far, the approach was heavily reliant on engineer experience and solutions for the same purpose have varied drastically in mass and design. By including the optimization process in designing truss structures the influence of engineer experience is modulated and high quality solutions are produced. This represents a great technological improvement in this field.

Authors of [1] made a comparison of sizing, topology and shape results for optimization of planar and space trusses to sequential optimization of the three criteria. Additionally they showed the results of optimizing simultaneously all three aspects and included those results as well. Their research showed great improvements in results of simultaneous optimization compared to initial models and single aspect optimization. The examples used in their research did not include Euler buckling constraints, making the results inapplicable in practice. The problem was further explored in [2] where authors compared structural optimization for sizing, topology, shape, separately, as well as their simultaneous combinations with and without the use of buckling constraints on a standard 10 bar truss example.

Researchers in [3] developed an adaptive dimensional search algorithm for truss sizing problems. The paper considers fixed slenderness ratios for tension and compression members instead of dynamic buckling constraints as well as stress and displacement constraints for all members.

In [4] authors showed the effects of adding buckling constraints to truss sizing optimization for minimizing mass. Results showed significantly larger weights of models compared to examples which do not have this constraint which have bars that do not meet buckling criteria, in some cases exceeding them by multiple times.

Researchers in [5] used discrete sizing variables with buckling constraints on various truss examples in select combinations of optimization types achieving reputable results. Papers [6-9] also successfully showed the implementation of dynamic buckling constraints in truss weight minimization problems.

Sizing optimization of planar and space trusses with an accent on the number of different cross-sections used was done by authors in [10] using buckling constraints and discrete cross-section variables.

The vast majority of research is focused on achieving optimal solutions without fear of having the solutions be practically inapplicable. The reason for such an approach is that the complexity of the problem which is observed when designing truss structures. This research is oriented in another direction compared to available literature. The major difference is in the practical perspective which is based on mapping potentially acceptable solutions and forming groups of optimal solutions for application in construction. From an optimal group, engineers can come to a conclusion on which solution should be accepted according to the use case. Aside from mapping, zones of unacceptable solutions are also available according to which practical constraint they do not meet. The main contribution of using this approach is that it simplifies and decreases the price of applicability of a structure, and significantly simplifies engineers' jobs.

2. PROBLEM DEFINITION

The basic concept behind this research is the mapping of acceptable and unacceptable solutions in designing an optimal 10 bar truss. The idea is to develop a completely new approach to optimizing truss structures which is practically oriented and where, based on obtained results an engineer could come to a conclusion which of the solutions will be accepted and produced.

In order to map solutions it is necessary to conduct structural optimization. The optimization is done in an original software developed in Rhino's Grasshopper using Karamba and Silvereye plugins. Here the authors separated the segments for solving sizing, topology and shape optimization. Aside from this constraints were developed to eliminate unusable solutions.

The methodology behind this new approach is used on the 10 bar truss problem in order to verify it and to show the significance of this methodology.

2.1. Minimal Weight Truss Optimization

The basic criteria of truss structural optimization is the minimization of weight. This effect is achieved through use of three basic aspects of structural optimization: sizing, shape and topology. In the general case the problem of structural optimization can be defined as follows:

$$\begin{cases} minW\left(A\right) = \sum_{i=1}^{i=n} \rho_i A_i l_i \text{ with } A = \left(A_1, \dots, A_n\right) \\ \text{subjected to} \begin{cases} A_{min} \le A_i \le A_{max} & \text{for } i = 1, \dots, n \\ \sigma_{min} \le \sigma_i \le \sigma_{max} & \text{for } i = 1, \dots, n \\ u_{min} \le u_j \le u_{max} & \text{for } j = 1, \dots, k \end{cases} \end{cases} \tag{1}$$

In this expression set: W is the weight of the truss, n is the number of truss elements, k is the number of nodes, l_i is the length of the i^{th} element, A_i is the area of the i^{th} element cross-section, σ_i is the stress of the i^{th} element, and u_j is the displacement of the j^{th} node.

In order to achieve results which can be applicable in practice constraints for compressed elements are added to the optimization problem. These constraints are for Euler critical buckling load, as shown in expression (4). The moment of inertia change in each iteration, due to the change of cross-sections making this a dynamic constraint. The addition of buckling constraints increases the complexity of the optimization problem meaningfully. Since in the expression for Euler buckling (2) the same areas figure as denominators on both sides of the expression, the critical force load (3) can be used as the buckling constraint to minimize necessary computation. The constraint then is derived as expression (4).

$$\begin{gathered} \sigma_{Ai}^{comp} \le \sigma_{Ki} \\ where \;\; \sigma_{Ai}^{comp} = \frac{F_{Ai}^{comp}}{A_i} \;\; and \;\; \sigma_{Ki} = \frac{F_{Ki}}{A_i} \end{gathered} \tag{2}$$

$$F_{Ki} = \frac{\pi^2 \cdot E_i \cdot I_i}{l_i^2} \tag{3}$$

$$\left|F_{Ai}^{comp}\right| \le F_{Ki} \text{ for } i = 1, \dots, n \tag{4}$$

In this expression set: σ_{Ai} is the axial compression stress of the i^{th} bar element, and σ_{Ki} is the critical buckling stress if the i^{th} element, F_{Ai}^{comp} is the axial compression force, F_{Ki} is Euler's critical load of the i^{th} element, E_i is the modulus of elasticity i^{th} element, and I_i is the minimum area moment of inertia of the cross section of the of the i^{th} element. The condition for compressed elements from equation (4) is added to the existing constraints from equation (1).

Another added constraint is the addition of minimal element length which can be used, which is determined by experience or design guidelines given in literature or corresponding standards. The mathematical formulation of this constraint is given as:

$$\begin{gathered} l_i \ge l_{\min} \quad for \quad i = 1, \dots, n \\ l_i = \sqrt{\left(x_b^i - x_a^i\right)^2 + \left(y_b^i - y_a^i\right)^2} \end{gathered} \tag{5}$$

The element length l_i is from the 1 to n range which is between nodes a and b with coordinates (x^i_a, y^i_a) and (x^i_b, y^i_b) in that order. Since existing node coordinate constraints implicitly define maximal element values, they are not necessary.

The use of continuous variables for cross-section dimensions give results which are practically impossible to produce. Aside from that, the resulting structures have all, or almost all, different cross sections which is irrational. Since dimensional tolerances for cold formed profiles are quite large, the specific dimensions achieved through the use of continuous variables would be impossible to produce, let alone guarantee. As these structures are usually at an optimum where even small divergences from their optimal dimensions result in an unstable structure, it can be concluded that the use of continuous cross-sectional variables is unacceptable for practical application, and will not be used in this research.

Instead, cross-section dimensions are selected from catalogues of stock sizes available on the market.

2.2. Example – 10 Bar Truss

The 10 bar truss problem's bar and node layout is a familiar one, as it is used in most research in the field of truss optimization (figure 1). Bar elements are Aluminum 6063-T5 with a Young modulus of 68947MPa, and density of 2.7g/cm^3. One load case is tested with a point loads of F=444.82kN, in the $-y$ direction in nodes 4 and 2. Constraints include a maximal displacement of ±0.0508m of all nodes in all directions, axial stress of ±172.3689MPa for all bars, and Euler buckling constraints for all bars.

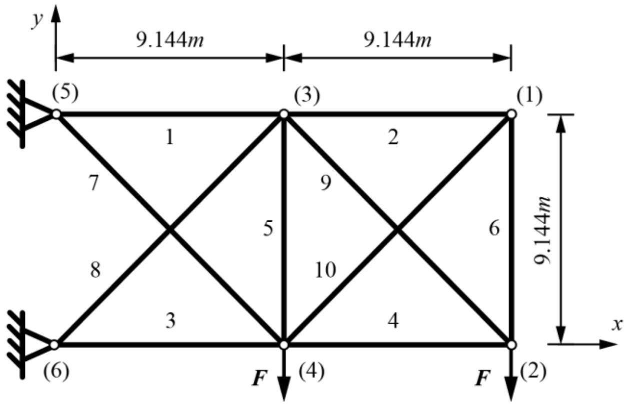

Fig.1. 10 bar truss – initial layout

This problem is intended for result verification in truss optimization development. Nodes 1 and 3 are the only nodes which have variable coordinates.

2.3. Optimization Method

Optimization is a process in which it is necessary to find the best solution in a given domain for a mathematically defined problem. For complex problems such as structural optimization this is only possible through the use of computers in order to achieve practical and applicable solutions. The best suited methods for optimization in this group of problems are heuristic methods due to their ability to achieve convergence with a small number of known facts. Aside from this, these methods allow for convergence regardless of whether the absolute optimum will be achieved which is its greatest advantage.

For the purposes of this research PSO optimization method was used which is integrated into the original software developed in Rhino's Grasshopper. The Particle swarm optimization (PSO) method is from the swarm intelligence based algorithm group and it has a significant implementation in solving complex optimization problems. Due to its exemplary characteristics it is used a lot and has numerous modifications [11]. The key characteristic of this method is that it searches across the entire acceptable domain and has only one phase, which simplifies and speeds up the optimization process. The operating principle is based on the principle of particle acceleration, the distance and position of a particle from the best value of a given particle (local best – $x_{p,i}$) and the position from the globally best particle (global best – $x_{g,i}$). Each of the positions of a particle in a given moment represents a potential solution of the goal function. Only the best position is accepted and it is carried over through an iterative optimization process. New solutions depend on the two aforementioned components, velocity and position. The position is defined by x_i, while velocity is represented by v_i. The number of positions and acceleration is n, depending on the total number of particles which are user defined. New values are acquired using expressions (6) and (7).

$$x_{new,i} = x_{old,i} + v_{new,i} \tag{6}$$

$$v_{new,i} = \omega \cdot v_{old,i} + c_p \cdot r_p (x_{p,i} - x_{x,i}) + c_g \cdot r_g (x_{g,i} - x_{x,i}) \tag{7}$$

where $i=1,2,...,N$, which represents the total population size. Constants c_p and c_g have valuse taken from literature to be 1.5. For random values r_p and r_p values are taken from a range of 0 to 1. The current position of a particle is represented with $x_{x,i}$. Intensity values for a particle is ω (inertia weight) and is obtained from expression (8) with values of $\omega_{max}=0.9$ and $\omega_{min}=0.9$ being suggested by literature.

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{Iteration_{\max}} \cdot Iteration \tag{8}$$

The developed software allows the use of the chosen optimization type and developed constraints. Constraints are set as penalty functions which eliminate unusable solutions. The Silvereye [12] operator for optimization uses PSO method.

3. RESULTS

A large number of simulations was conducted in order to map solutions using the developed methodology on the 10 bar truss problem. For the initial layout two cross-sections were chosen to be optimized, namely full circular cross-sections D=240mm and D=250mm. Figure 1 was used as a benchmark a weight of 13019.500 kg with a cross-section area of 452.389cm^2 for all bars (or a diameter of 240mm) and a weight of 14202.758kg with a cross-section area of 490.874cm^2 for all bars (or a diameter of 250mm). These model had their topology optimized and a new weights of 8089.269kg and 8319.783kg was achieved for the 240 and 250 mm models respectively. was achieved. Compared to the initial model, where the total number of bars was 10, the topologically optimized solutions consists of only 6 bars.

The topologically optimized solution layouts are shown in figure 2. The condition was that nodes with supports and loads must exist in the solution in the same location as the initial layout.

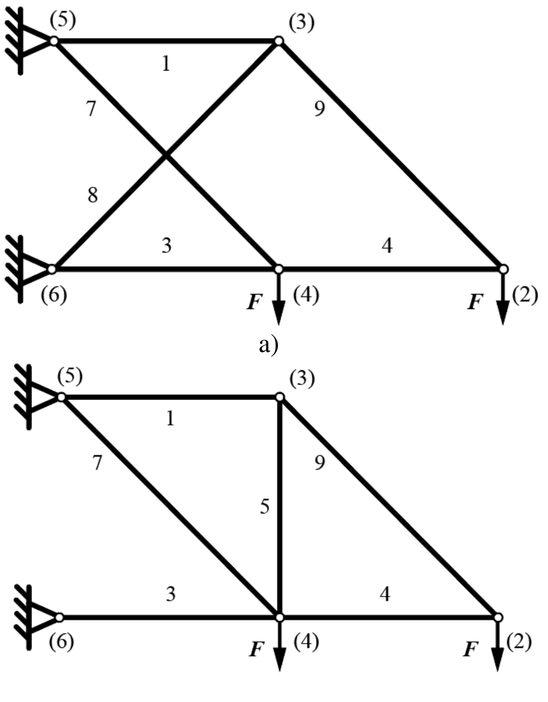

Fig.2. 10 bar truss – optimal topology solution layouts for a)D240 and b)D250 cross-sections

Based on the use of the topological solution the next optimization in the sequence was conducted, and that is shape optimization. Due to the support and load nodes having to maintain the same position, only node (3) can achieve a new position which decreases the overall length of elements1, 8 and 9, for the D240, and 1, 5 and 9 for the D250 model. This decrease leads to a solution with a lower weight of 7319.658kg for the D240 and 7271.918kg for the D250 model. A comparison of both 240 and D50 models in their initial, topology optimized and then shape optimized weights is shown in figure 3. Additionally shown in figure 3 are the shape and simultaneous topology and shape optimization results from literature for the D240 layout.

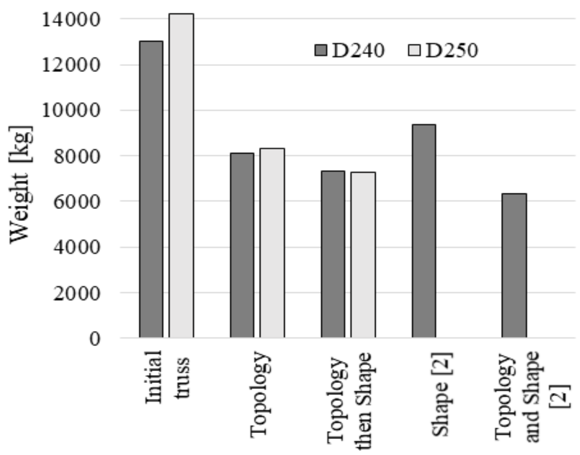

Fig.3. Mass comparison for the initial model and topology and shape optimized models.

The simultaneously optimized results from literature have a different topology than the model presented here as the removed elements in that case are 2, 6, 7 and 10.

The achieved optimal values are unique and represent a global optimum for the truss weight minimization problem which meet all constraint criteria. Based on the solutions, in practice the trusses should be constructed in exactly that specific way. Due to numerous issues in construction, and mostly die to precision and tolerances in manufacturing, it is extremely difficult to create a truss with the exact node coordinates. This research is oriented towards mapping the space which is acceptable and the direction of tolerated deviation, as well as identifying positions which may not be taken up by the node as it would lead to breaching constraints.

Through the process of optimization a large search space has been observed. Among the solutions are acceptable and unacceptable solutions. Groups of solutions for the D240 model are mapped in figure 4 and solutions for D250 are shown in figure 5.

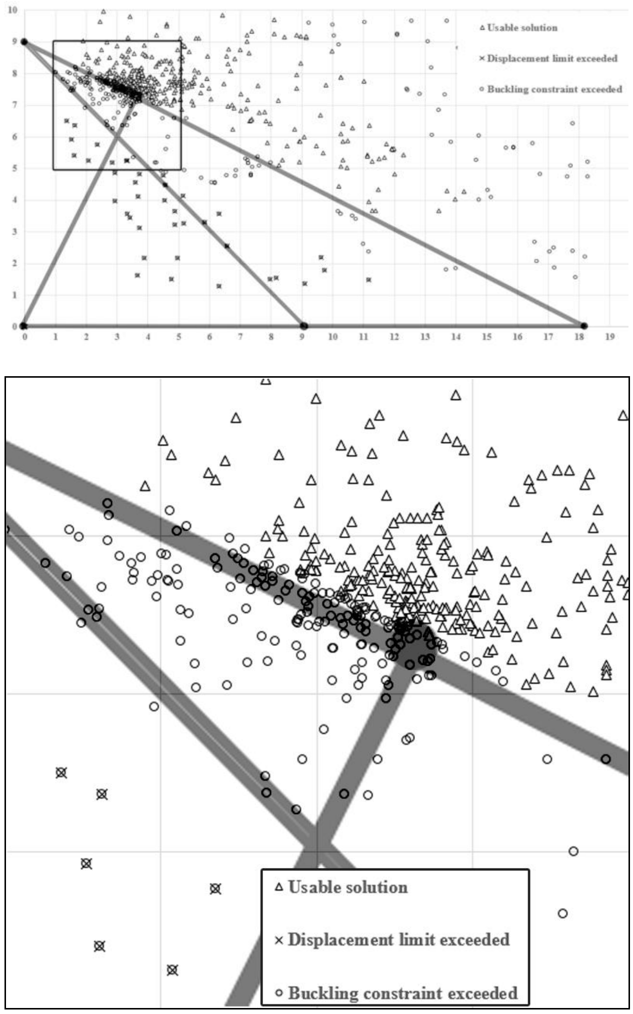

Fig.4. Mapping usable zone with shape optimization for the D240 model

The diagram's axes are represented by lengths in meters, and the characteristic positions of the node are given for the global optimum. The global optimum is on the very border nearest to the unacceptable solutions. The coordinates of Node 3 are given in table 1.

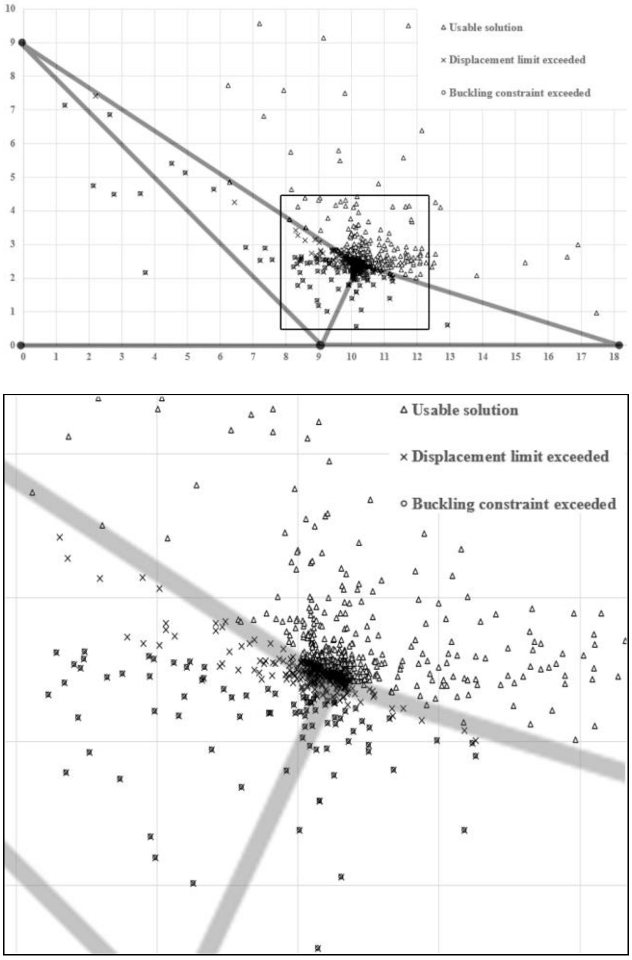

Fig.5. Mapping usable zone with shape optimization for the D250 model

Table 1. Optimal position of Node 3

Coordinate	*x* [m]	*y* [m]
D240	3.725	7.371
D250	10.310	2.456

Every usable solution from fig.ures 4 and 5 represents an acceptable solution for producing that truss. The positions shown in these figures are only the tested solutions which came up in the optimization process which allow us to identify the acceptable zone and differentiate them from zones of different constraint breaches. Values of weight are in the range between the initial and optimal solution for all acceptable solutions of the D240 model and exceed initial weight in some areas of the D250 model.

Figures 6 and 7 show the approximate areas in which placing node (3) would be acceptable and the approximate weight range of trusses with node (3) in that area for examples D240 and D250 respectively. These areas are created by repeating the optimization process and viewing only the acceptable solution points. The illustration is based on a small number of samples, and a greater number of points would be needed to find the exact boundaries of each weight range.

For the D240 example there is a very narrow area in which solutions do not breach constraints and the areas are relatively linear, with some exceptions.

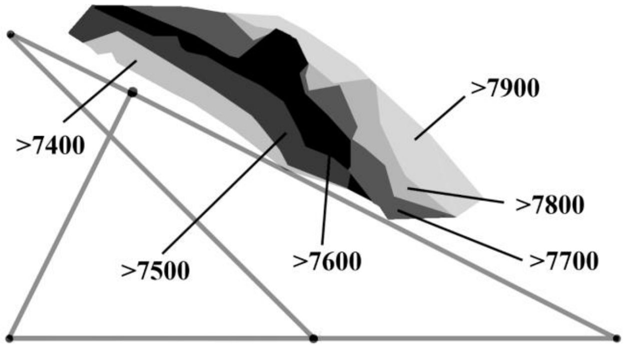

Fig.6. Mapping weight zones in the acceptable range of node 3 for the D240 model

For the D250 example a small area near the initial position of node (3) and towards the far left and right of there has coordinates which would lead to an increase of weight compared to the topologically optimized model.

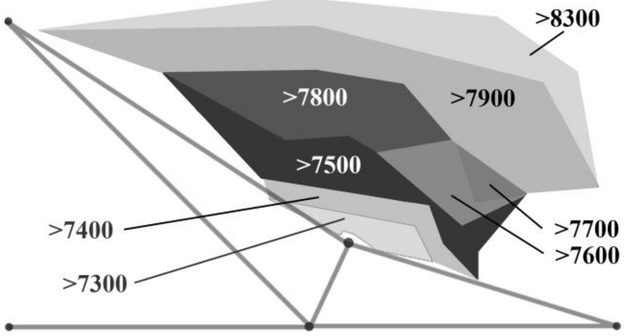

Fig.7. Mapping weight zones in the acceptable range of node 3 for the D250 model

It can be seen that the range of possible positions for node (3) is quite large and that the structure weight does not have a radial change from the optimal position outward. Just rounding up to coordinates (10.5m; 2.6m) increases the weight from 7271.918kg to 7288.578kg. This is not a drastic change, and even rounding down to (10.3m; 2.5m) changes the weight to 7275.369kg. The area where node (3) can be placed and have the weight under 7300kg is very small, however keeping the weight under 7400kg gives much more range while still maintaining a lower weight than the just topologically optimized solution.

This approach allows the engineer to choose the best solution from an acceptable area and not overly compromise on weight while avoiding the possibility of the structure crossing the boundary between acceptable solutions and breaching a constraint due to production tolerance deviations or small errors in assembly.

Results confirm that the new developed approach in structural optimization of truss structures allows easier construction with lower costs and prevents more possible consequences caused by human error.

4. CONCLUSION

Modern engineering approaches imply a use of intelligent technologies and the use of computers in all phases of a products lifecycle. One of the most important segments of intelligent technologies is optimization. The integration and implementation of optimization with other computer tools in the early development phases gives the best results in terms of performance for the lowest cost.

This research presents a new methodology with a practically oriented approach to truss structural optimization. The developed methodology is applicable for any truss. For the purposes of this research, in order to verify results, a typical 10 bar truss problem was used as an example. For the initial solution of the problem two options were given with a different cross-section dimension for each model (one with a diameter of 240mm and the other 250mm). These models produced two different optimal topologies which were then used for shape optimization. The different cross-sections resulted in two different topology layouts of similar weight. The shape optimization results were also less than 10% different from their different cross-section counterparts. The optimal solutions of the 240mm cross-section model was compared to results from literature which used a simultaneous approach rather than a sequential one as was the case here. The consecutive approach yields a ~16% greater weight and has a different topology compared to the simultaneous model.

The most important segment of this research was mapping areas which would foster node positions leading to acceptable solutions. Zones were roughly mapped to also show the changes in weight depending on node positions in the acceptable domain. The boundaries of these zones also represent limits past which one or more constraints can be breached. Using the mapped results an optimized structure of a lower weight can be created and can have drastically higher tolerances in production and assembly which can additionally save on costs. This research is a precursor for further research which will take into account the effects of dimensional and shape tolerances in bar element production in structural optimization.

REFERENCES

[1] Müller T. E., and Klashorst E. v. d., "A Quantitative Comparison Between Size, Shape, Topology and Simultaneous Optimization for Truss Structures", Latin American Journal of Solids and Structures, 14, 2221-2242, 2017.

[2] Petrovic N., Kostic N., and Marjanovic N., "Comparison of Approaches to 10 Bar Truss Structural Optimization With Included Buckling Constraints", Applied Engineering Letters, 2, 98-103, 2017.

[3] Hasançebi O., and Azad S. K., "Adaptive dimensional search: A new metaheuristic algorithm for discrete truss sizing optimization", Computers & Structures, 154, 1-16, 2015.

[4] Petrovic N., Marjanovic N., Kostic N., Blagojevic M., Matejic M., and Troha S., "Effects of introducing dynamic constraints for buckling to truss sizing optimization problems", FME Transaction, 46, 117-123, 2018.

[5] Petrović N., Kostić N., Marjanović N., Živković J., and Cofaru I. I., "Effects of Structural Optimization on Practical Roof Truss Construction", Applied Engineering Letters, 5, 39-45, 2020.

[6] Shahabsafa M., Mohammad-Nezhad A., Terlaky T., Zuluaga L., He S., Hwang J. T., and Martins J. R. R. A., "A novel approach to discrete truss design problems using mixed integer neighborhood search", Structural and Multidisciplinary Optimization, 58, 2411-2429, 2018.

[7] Cai Q., Feng R., and Zhang Z., "Topology optimization of truss structure considering nodal stability and local buckling stability", Structures, 40, 64-73, 2022.

[8] He L., Li Q., Gilbert M., Shepherd P., Rankine C., Pritchard T., and Reale V., "Optimization-driven conceptual design of truss structures in a parametric modelling environment", Structures, 37, 469-482, 2022.

[9] Jawad F. K. J., Ozturk C., Dansheng W., Mahmood M., Al-Azzawi O., and Al-Jemely A., "Sizing and layout optimization of truss structures with artificial bee colony algorithm", Structures, 30, 546-559, 2021.

[10] Petrović N., Marjanović V., Kostić N., Marjanović N., and Viorel Dragoi M., "Means and Effects of Constraining the Number of Used Cross-Sections in Truss Sizing Optimization", Transactions of FAMENA, 44, 2020.

[11] Harsono K., Prayogo D., Prasetyo K. E., Wong F. T., and Tjandra D., "Comparative Study of Particle Swarm Optimization Algorithms in Solving Size, Topology, and Shape Optimization", Journal of Physics: Conference Series, 1625, 012015, 2020.

[12] Cichocka J. M., Migalska A., Browne W. N., and Rodriguez E., "SILVEREYE – The Implementation of Particle Swarm Optimization Algorithm in a Design Optimization Tool", 724, 151-169, 2017.

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BUCKLING ANALYSIS OF SIMPLY SUPPORTED SQUARE SYMMETRIC LAMINATED COMPOSITE PLATE

Dejan JEREMIĆ
Nebojša RADIĆ
Nikola VUČETIĆ

Abstract: *The present work deals about a buckling analysis of simply supported symmetric composite plate with four layers. It is assumed that composite plate is surrounded by external elastic fundation. Composite plate is modeled by the finite element method and subjected to biaxial compression load. Governing equations are derived based on Classical Laminated Plate Theory (CLPT) and computed critical buckling loads were compared with numerical results.*

Keywords: *buckling; symmetric composite plate; orientation of layers; compression load*

1. INTRODUCTION

A composite laminate is composed of reinforcement (fibres, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). A laminate is called symmetric if the material angle, and the thickness of plies are the same above and below the midplane. The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix.
To use the laminated composite plates efficiently, it is necessary to develop appropriate analysis theories to predict accurately their structural and dynamical behavior. The analysis of the behavior of the laminated plates is an active research area because of their complex behavior. The structural instability becomes an important concern in a reliable design of composite plates. Several studies on laminated plates stability were concentrated on rectangular plates [1-3]. It is known that buckling strength of the rectangular plates depends on the boundary conditions, plies orientation and geometrical ratio [2-4]. The thin composites structures which are largely used become unstable when they are subjected to mechanical or thermal loadings which leads to buckling. The buckling of the composite plates is a very complicated subject and more details can be seen in references [1-4]. To predict buckling load and deformation mode of a structure, the linear analysis can be used as an evaluation technique [5]. The buckling analysis of rectangular laminated composite plate with and without cutouts for the effects of fiber angle orientation and cutout shapes on critical buckling load are determined [12]. The effect of aspect ratio, orthotropic ratio and fiber orientation for antisymmetric laminated composite plates subjected to in plane loading are discussed to obtain critical buckling load [13].
The majority of the investigations on laminated plates utilize either the classical lamination plate theory (CLPT), or the first-order shear deformation theory (FSDT). Various geometries of the plates subjected to compressive load are studied. In [10] buckling analysis of the laminated composites is performed by using finite element analysis software ANSYS. Buckling analysis of a simply supported rectangular plate subjected to various types of non-uniform compressive loads has been studied [15]. The effect of fibre orientation on buckling behavior in a rectangular composite laminate with central circular hole under uniform in-plane loading has been studied by using finite element method [16].
In this paper, buckling behavior of symmetric laminated composite plates under biaxial compression load using ANSYS software is studied. The main contribution of this work is to perform a composite laminated plates analysis by using the Classical Laminated Plate Theory (CLPT) and ANSYS ACP. The ANSYS results are validated with the results predicted by classical laminated plate theory. The composite plate is modeled as shell model and then it is loaded by compression load. Then the obtained critical loads are compared for two different orientations of layers calculated using CLPT.
The laminated composite plates are thin shell elements composed of fibre lamination and epoxy resin is used to bond the lamina. The strength of these composite plates depended on type and properties of fibre material used along with epoxy resin. In structural designing field ANSYS, COSMOS, ABAQUS and so on are the most used finite element analysis software's. ANSYS is most

trusted finite element software as it provides ease of work to analyse the laminated composite plates under buckling in biaxial loading. Where as in experimental study the biaxial loading is complicate to perform and requires energy and resources.

2. THEORETICAL FORMULATION

The buckling analysis of the symmetric square composite plate with 4 plies made of two types of materials and two different layouts of plies is performed (Figure 1).

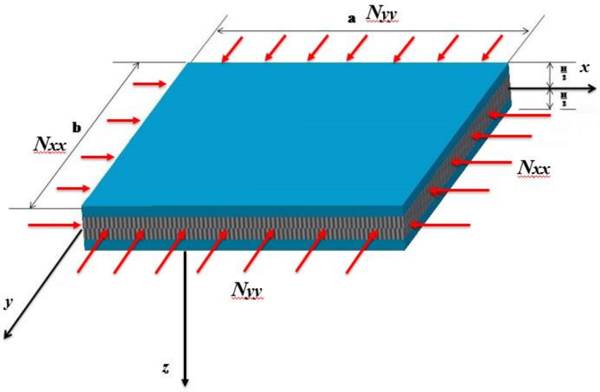

Fig.1. Symmetric square composite plate with 4 plies

The material properties of composite plate are kevlar 49/CE 3305 as material 1 (M1): E1 = 82 GPa, E2 = 4 GPa, G12 = 2.8 GPa, υ_{12} = 0.25 and graphite-epoxy AS-1/3501-5A as material 2 (M2): E1 = 127.6 GPa, E2 = 11 GPa, G12 = 4.5 GPa, υ_{12} = 0.25

The thickness of one ply is h = 0.25 mm. The symmetric orientations of plies α in composite are defined as M10/ M230/M230/M10 and M20/M130/M130/M20.

For laminates of total thickness of 1mm with four sheets of individual thickness of 0.25mm, bending stiffness matrix D has the following form [8]:

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{N}\left(\overline{Q}_{ij}\right)^{k}\left(h_k^3 - h_{k-1}^3\right)$$

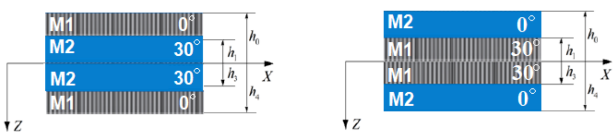

Fig.2. Symmetric orientation of plies and bending stiffness matrix

Based on the above material properties and using the MATLAB software package, bending stiffness matrix for selected laminate schemes $\theta = 0°, 30°$ are obtained.

$$[D] = \begin{bmatrix} 6,7954 & 0,3167 & 0,3990 \\ 0,3167 & 0,4800 & 0,1298 \\ 0,3990 & 0,1298 & 0,4841 \end{bmatrix} \qquad [D] = \begin{bmatrix} 9,8649 & 0,3548 & 0,2588 \\ 0,3548 & 0,9093 & 0,0941 \\ 0,2588 & 0,0941 & 0,5000 \end{bmatrix}$$

2.1. Governing equations of biaxially compressed composite plate

The governing equation for biaxially compressed orthotropic composite plate [14], which is based on Classical Laminated Plate Theory (CLPT), have following form

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 2\left(D_{12} + 2D_{66}\right)\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} + N_x\frac{\partial^2 w}{\partial x^2} + N_y\frac{\partial^2 w}{\partial y^2} = 0 \tag{1}$$

We assume that composite plate is biaxially compressed in the directions of x and y axes, N_x=N_y. Now we can define compression ratio which equals the ratio between the forces acting in y and x directions

$$\delta = \frac{N_{yy}}{N_{xx}} \rightarrow N_{yy} = \delta N_{xx} \tag{2}$$

Substitution of equation (2) in equation (1) we derive the general form of governing equation

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 2\left(D_{12} + 2D_{66}\right)\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} + N_x\left(\frac{\partial^2 w}{\partial x^2} + \delta\frac{\partial^2 w}{\partial y^2}\right) = 0 \tag{3}$$

It is assumed that all edges on composite plate are simply supported. This means that both the displacements and moments at the composite plate edges are zero. This can be expressed by following equations

$$w_i(0,y,t) = 0, \quad w_i(a,y,t) = 0, \quad w_i(x,0,t) = 0,$$
$$w_i(x,b,t) = 0 \qquad i = 1,2 \tag{4}$$
$$M_i(0,y,t) = 0, \quad M_i(a,y,t) = 0, \quad M_i(x,0,t) = 0, \quad M_i(x,b,t) = 0 \tag{5}$$

We assume that the buckling mode of the composites system as

$$w = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{mn}\sin\left(\alpha x\right)\sin\left(\beta y\right) \tag{6}$$

In the upper equation:

$$\alpha = \frac{m\pi}{a},$$
$$\beta = \frac{n\pi}{b} \tag{7}$$

where m and n are the half wave numbers.

Substituting equation (6) into equation (3), we get critical buckling load

$$N_{cr} = \frac{D_{11}\alpha^4 + 2(D_{12} + 2D_{66})\alpha^2\beta^2 + D_{22}\beta^4}{(\alpha^2 + \delta\beta^2)} \tag{8}$$

Each composite plate had the length, **a** and width **b**. We assume that composite plates are biaxially compressed by forces N_{xx} and N_{yy} in the directions of x and y axes (Figure 3).

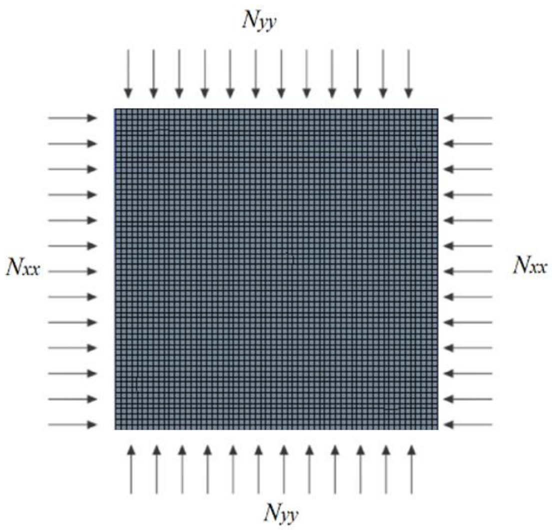

Fig.3. Composite plate loaded by biaxial compression load

3. RESULTS AND DISCUSSION

Non-dimensional buckling load was calculated for the number of half waves m=1, n=1 and m=2, n=2, while the compression ratio was δ=1. The thickness of one composite plate is h = 0,25 mm, while the length and width take values a=0,3m and b=0,3 (square plate). We investigated buckling behavior of square symmetric composite plate under biaxial compression load using Classical Laminated Plate Theory (CLPT) and computed critical buckling loads were compared with results obtained in ANSYS 19.2 ACP (Ansys Composites PrepPost). The present ANSYS model validation has been obtained for two different laminated composite plates and are presented in Table 1.

Table 1. Validate the ANSYS results with reference [9] for 4-layer symmetric square plate

Biaxial compression		***Ncr***		
COMPOSITE PLATE	HALF WAVE NUMBERS	CLPT	ANSYS	% error
M10/M230/M230 /M10	m=1 n=1	7,1496	5,288	26
	m=2 n=2	28,5982	21,673	24
M20/M130/M130 /M20	m=1 n=1	6,7451	7,0868	4,82
	m=2 n=2	26,980	28,738	6,11

The present ANSYS ACP model (Figure 4 and Figure 5) is being validate by comparing the results with references [9] by taking the same material properties, geometrical parameters and boundary conditions.
In Table 1 the present ANSYS results are showing good agreement for laminate M20/M130/M130/M20 and the values are max 6,11% error compared to the reference [9]. The values for laminate M10/M230/M230/M10 are higher with max 26% error compared to the reference [9]. It is because of the fact that the present model is developed in the finite element analysis software ANSYS whereas in the reference the model is developed based on analytical solution using CLPT. For biaxial compressive loading the values are obtained for all edges simply supported (SSSS) boundary condition. The critical buckling load of the composite plate is almost the same for all two laminates

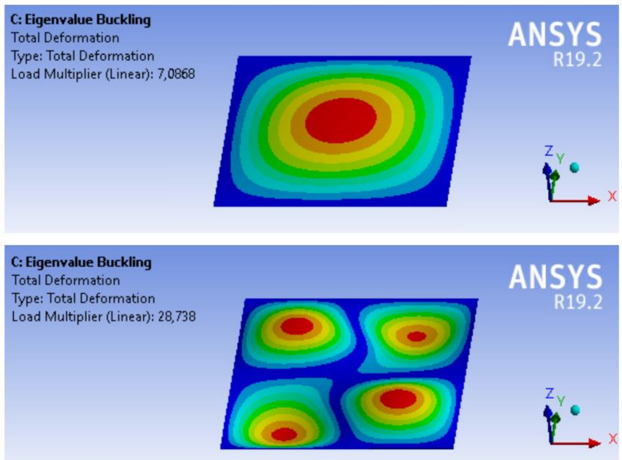

Fig.4. ANSYS results for laminate M10/M230/M230/M10

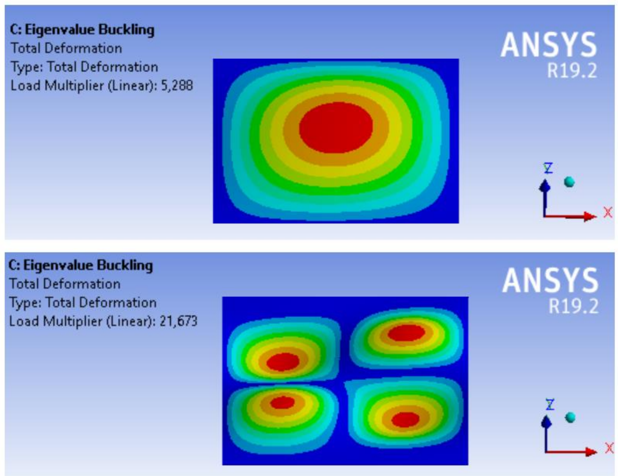

Fig.5. ANSYS results for laminate M20/M130/M130/M20

4. CONCLUSION

The paper studied the buckling behavior of the square symmetric composite plates with two different layer orientations and four layers. The all composite plates were modeled using finite element method in ANSYS 19.2 ACP. The finite element model of composite plate consisted from shell elements, which had defined the material of composite plate, the thickness of composite plate and layout of layers. The composite plates were loaded by biaxial compression load. The boundary conditions on the parallel edges with *x* and *y* were applied. The computed critical buckling loads for all configurations showed that:
- the orientations of composite layers effect the value of critical buckling load, for example the composite plate with orientation of layers M20/M130/M130/ M20 is more sensitive to compression load than the composite plate with orientation of layers M10/M230/M230/ M10

- the buckling shapes are slightly effected by position of layer in composite plate.
-for value of half wave m=2 and n=2 we get higher value of non-dimensional buckling load.
It has been shown that with the change of layer position and angle of fiber orientation the value of the non-dimensioning critical load is changed. Laminate have different minimum and maximum values of non-dimensional critical force.

REFERENCES

[1] Kaw, K.: *Mechanics of Composite Materials*, 2nd Edition, Taylor & Francis, Group, CRC Press, New York, 2006
[2] Muc, A.: Optimal fibre orientation for simply-supported angle-ply plates under biaxial compression, *Composite Structures*, 9:161–72, 1988
[3] Nemeth, MP.: Buckling behavior of compression-loaded symmetrically laminated angle-ply plates with holes, *AIAA Journal,* 26:330–6, 1988
[4] Zor, M., Sen, F., Toygar, ME.: An investigation of square delamination effects on the buckling behavior of laminated composite plates with a square hole by using three-dimensional FEM analysis, *J Reinf Plast Compos*, 24:1119–30, 2005
[5] Shufrin, I., Rabinovitch, O., Eisenberger, M.: Buckling of laminated plates with general boundary conditions under combined compression, tension, and shear-A semi-analytical solution, *Thin-Wall Struct*, 46:925–38, 2008
[6] Reddy, JN.: *Mechanics of Laminated Composite Plates and Shells: Theory and Analysis*, CRC Press LLC, London and New York, 2004
[7] Spencer, A.J.M.: *Constitutive Theory for Strongly Anisotropic Solids in Continuum Theory of the Mechanics of Fibre Reinforced Composites*, Springer-Verlag, Wien, 1984
[8] Powell, P.C.: *Engineering with Fibre-Polymers Laminates*, Chapman & Hall, England, 1994.
[9] Jeremić, D.: Analiza stabilnosti laminantnih kompozitnih ploča, Master Thesis, East Sarajevo, 2013
[10] Buket Okutan Baba and AysunBaltaci*:* Buckling characteristicsof symmetrically and antisymmetrically laminated compositeplates with central cutout, *Applayed Composite Materials*, 14 pp. 265–276, 2007
[11] Rund Al-Masri and Hayder A. Rasheed: Analytical and Finite Element Buckling Solutions of Fixed-Fixed Anisotropic Laminated Composite Wide Plates Under Axial, *SPE ANTEC Anaheim*, pp. 550-557, 2017
[12] Ramesh N. R., Thyagaraj. N. R., Prema Kumar W. P., and Prathap Kumar M. T.: Experimental and Finite Element Studies on Buckling of Laminated E-Glass Woven Fabric Epoxy Composite Plates, *International Journal of Engineering Research & Technology (IJERT)* ISSN: 2278-0181 Vol. 3 Issue 7, 2014
[13] Liecheng Sun., P.E., M.ASCE; and Issam E. Harik., M.ASCE.Buckling of Stiffened Antisymmetric Laminated Plates, *Journal of Engineering Mechanics*, Vol. 139, No. 8, August 1, ISSN 0733-9399/2013/8-1110–1123, 2013
[14] Priyanka Dhurvey and N D Mittal.: Buckling Behavior of an Orthotropic Composite Laminate using Finite Element Analysis, *International Journal of Scientific Engineering and Technology*, ISSN : 2277-1581, Volume No.1, Issue No.4, pp. : 93-95, 2012
[15] Jana P., Bhaskar K.: Stability analysis of simply supported rectangular plates under non-uniform uniaxial compression using rigorous and approximate plane stress solutions, *Thin-Walled structures*, 44, pp. 507-516, 2006
[16] Priyanka Dhurvey and Mittal N. D.: Buckling Behavior of an Orthotropic Composite Laminate using Finite Element Analysis, *International Journal of Scientific Engineering and Technology*, ISSN : 2277-1581, Volume No.1, Issue No.4, pp : 93-95, 2012

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ANALYZING THE BARRIERS RELATED TO SMART MANUFACTURING SYSTEMS UNDER NEUTROSOPHIC ENVIRONMENT

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Selçuk KORUCUK
Çağlar KARAMAŞA

Abstract: *More productive processes have come into the forefront with flexible production, cost effectiveness and business process improvement through developing technology. Smart systems have gained more importance in information society via Industry 4.0 and the smart concept is emphasized for innovative manufacturing systems. In other words, competitive power for businesses is being provided with integrated innovative automations and digitalized solutions. Accordingly the usage of smart manufacturing systems in providing efficient and exigible manufacturing process can be considered as critical components for businesses. But businesses encounter various barriers in transition process and applying smart manufacturing systems. With respect to productivity and efficiency, it is important and necessary for businesses to remove barriers or reduce them to the lowest level. In this study it is aimed to determine and prioritize the barriers related to smart manufacturing systems for plastic industry enterprises operated in Samsun via Neutrosophic AHP method. According to the findings cost of smart manufacturing systems was found as the most important barrier in terms of the judgments of experts. On the other hand top management's negative viewpoint towards smart systems was obtained as the least important barrier related to smart manufacturing systems.*

Keywords: *smart manufacturing; barriers to smart manufacturing systems; neutrosophic AHP*

1. INTRODUCTION

The most commonly used performance indicator in manufacturing enterprises, as well as in all sectors, is efficiency, which is defined as the effective use of raw materials, capital, energy, land, and information resources required for the introduction of various goods and services in enterprises. Efficiency, on the other hand, is defined as producing more with a given amount of input or obtaining a given output with a given amount of input [12,9]. Smart production systems are an indicator of increased efficiency and performance in businesses. High-value-added production opportunities are provided by this production model. In other words, smart manufacturing has a positive impact on employment, added value, resource efficiency, competitiveness, trade, financial stability, and economic welfare [6].
Smart production, according to [5], has a structure that radically transforms Industry 4.0 manufacturing systems. This transformation is made possible by Industry 4.0 technologies. Factories that have been modernized with these technologies are referred to as smart factories, and production that has been realized with these technologies is referred to as production realized with these technologies. Smart manufacturing systems, on the other hand, link all aspects of production, including supply chain, production, product, logistics, and service [3]. Because of their advanced automation, smart production systems, in particular, enable high efficiency and flexible production processes in production [7]. At the same time, because of its smart manufacturing processes, it provides greater access to data across the entire supply chain network.
Smart manufacturing systems help to increase productivity while lowering costs. Another effect of cost reduction is reflected in prices. Smart manufacturing systems enable the establishment of a transparent and flexible manufacturing system. When viewed from a macroeconomic standpoint, it is possible to conclude that the innovative production style based on smart production will have a positive impact on long-term development. Smart manufacturing technologies can help to reduce the use of unnecessary raw materials and resources. At the same time, businesses that produce environmentally friendly products now see this as a strategic value and are revising their marketing strategies to reflect this [4].
However, there are a number of barriers to the implementation of smart manufacturing systems in

businesses. These obstacles are generally expressed as the problem of leaving the traditional production method, lack of technological infrastructure, senior management's negative perspective on smart systems, unemployment problems that may occur with the use of smart manufacturing systems, cost of smart manufacturing systems, technology intensive business process planning problem, anxiety against smart manufacturing systems (such as cyber-attack), the problem of skilled workforce for smart manufacturing systems and the presence of unexpected stops and failures in smart devices [1,4]. In this context, the literature review on smart manufacturing and smart manufacturing systems is given below.

According to [10], relevant standards on which future smart manufacturing systems will be based are lacking, and current standards should be reviewed for better understanding. [8] used Time Series Analysis to study the concept of smart manufacturing and basic technologies and included various definitions of smart manufacturing systems in their studies. [2] defined smart manufacturing as factories where workers, machines, and resources can easily communicate and objects in the virtual and physical worlds can be connected to each other. [15] studied SMEs and large corporations in South Korea and Sweden to see how they embody the concept of smart manufacturing. [16] examined the use of technologies such as smart manufacturing, cloud services, big data, and analytics and discovered that industry 4.0 is critical to smart manufacturing. [11] identified the challenges that businesses faced as they transitioned to the smart manufacturing model. [5] investigated the impact of "Smart Manufacturing," which was implemented with the industry 4.0 vision, on business performance. In the context of Industry 4.0, [14] proposed a model for smart manufacturing system integration in apparel businesses.

At this point, the aim is to discover and rank the barriers to smart production systems for plastic industry enterprises in Samsun province by using multi-criteria decision-making (MCDM) methods. The factors obtained from the literature review were evaluated for this purpose by using the Neutrosophic AHP method, which is one of the MCDM methods. The theoretical explanations of the Neutrophic AHP method, which constitutes the study's method, will be expressed in the following sections of the study, and information about the findings by applying the method in Samsun will be provided. The final section of the study includes the conclusion, limitations of the study, and suggestions.

2. METHODOLOGY

2.1. Neutrosophic Set

Neutrosophic Sets (NS) are introduced by [18] with having the degree of truth, indeterminacy, and falsity membership functions that are independent. Neutrosophic sets provide an efficient and flexible approach for assessing alternatives by using these membership functions.

A universe of discourse can be shown as U and $x\in U$. N as NS can be identified by truth $T_N(x)$, indeterminacy $I_N(x)$and falsity membership functions $F_N(x)$, and represented as $N=\{<x:T_N(x), I_N(x),F_N(x)>x\in U\}$. Also, the functions of $T_N(x)$, $I_N(x)$ and $F_N(x)$ are real standard or real nonstandard subsets of $]0^-,1^+[$and can be presented as $T,I,F:U\rightarrow]0^-,1^+[$. The sum of the functions of $T_N(x)$, $I_N(x)$ and $F_N(x)$ can be written as $0^- \leq supT_N(x)+supI_N(x)+supF_N(x)\leq 3^+$[22].

The complement of NS N is represented by N^C and described as below:

$$T_N^C(x) = 1^+ \ominus T_N(x), \tag{1}$$

$$I_N^C(x) = 1^+ \ominus I_N(x), \tag{2}$$

$$F_N^C(x) = 1^+ \ominus F_N(x) \text{ for all } x \in U. \tag{3}$$

N as NS is contained in other NS V shows, $N\subseteq V$ if and only if $infT_N(x)\leq infT_V(x)$, $supT_N(x)\leq supT_V(x)$, $infI_N(x)\geq infI_V(x)$, $supI_N(x)\geq supI_V(x)$, $infF_N(x)\geq infF_V(x)$, $supF_N(x)\geq supF_V(x)$ for all $x\in U$ [17,19].

2.2. Single Valued Neutrosophic Sets (SVNS)

SVNS are developed by [24] for solving real-life problems in an environment having inconsistent, indeterminate and incomplete information. The interval of [0,1] are handled for real-life applications rather than]0^- ,1^+[. A universe of discourse can be represented as U and $x\in U$. A SVNS C in U can be described by truth $T_C(x)$, indeterminacy $I_C(x)$ and falsity membership functions $F_C(x)$. A SVNS C can be indicated as $C = \int_x < T_C(x), I_C(x), F_C(x) > / x : x\in U$ for continuous values of U. On the other hand, a SVNS C can be shown as $C = \sum_{i=1}^{n}\int_x < T_C(x), I_C(x), F_C(x) > / x_i : x_i\in U$ for discrete values of U [17,19,22]. $T_C(x)$, $I_C(x)$ and $F_C(x)$ functions are real standard subsets of [0,1] that is $T_C(x):U\rightarrow[0,1]$, $I_C(x):U\rightarrow[0,1]$, and $F_C(x):U\rightarrow[0,1]$. Besides, the sum of $T_C(x)$, $I_C(x)$ and $F_C(x)$, are in [0,3] and this can be showns as $0\leq T_B(x)+ I_B(x)+ F_B(x)\leq 3$ [19].

Let a single-valued neutrosophic triangular number $\tilde{a} = <(a_1, a_2, a_3); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}}>$ is a special neutrosophic set on R. In addition $\alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}}\in [0,1]$ and $a_1,a_2,a_3\in R$ where $a_1\leq a_2\leq a_3$.Truth, indeterminacy and falsity membership functions of this number can be obtained as follows [20,22]:

$$T_{\tilde{a}}(x) = \begin{cases} \alpha_{\tilde{a}}\left(\frac{x-a_1}{a_2-a_1}\right) & (a_1 \leq x \leq a_2) \\ \alpha_{\tilde{a}} & (x = a_2) \\ \alpha_{\tilde{a}}\left(\frac{a_3-x}{a_3-a_2}\right) & (a_2 < x \leq a_3) \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$I_{\tilde{a}}(x) = \begin{cases} \left(\frac{a_2-x+\theta_{\tilde{a}}(x-a_1)}{a_2-a_1}\right) & (a_1 \leq x \leq a_2) \\ \theta_{\tilde{a}} & (x = a_2) \\ \left(\frac{x-a_2+\theta_{\tilde{a}}(a_3-x)}{a_3-a_2}\right) & (a_2 < x \leq a_3) \\ 1 & \text{otherwise} \end{cases} \tag{5}$$

$$F_{\tilde{a}}(x) = \begin{cases} \left(\frac{a_2-x+\beta_{\tilde{a}}(x-a_1)}{a_2-a_1}\right) & (a_1 \leq x \leq a_2) \\ \beta_{\tilde{a}} & (x = a_2) \\ \left(\frac{x-a_2+\beta_{\tilde{a}}(a_3-x)}{a_3-a_2}\right) & (a_2 < x \leq a_3) \\ 1 & \text{otherwise} \end{cases} \tag{6}$$

Maximum truth, minimum indeterminacy and minimum falsity membership degrees are indicated by $\alpha_{\tilde{a}}$, $\theta_{\tilde{a}}$ and $\beta_{\tilde{a}}$ respectively according to the Eqs. (4-6).

Suppose $\tilde{a}$ = < (a_1, a_2, a_3); $\alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}}$ > and $\tilde{n}$ = < (n_1, n_2, n_3); $\alpha_{\tilde{n}}, \theta_{\tilde{n}}, \beta_{\tilde{n}}$ > as two single-valued triangular neutrosophic numbers and $\lambda \neq 0$ as a real number. Handling the above-mentioned conditions, addition of two single-valued triangular neutrosophic numbers are shown as follows [20,22]:

$$\tilde{a} + \tilde{n} = \langle (a_1 + n_1, a_2 + n_2, a_3 + n_3); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \rangle. \tag{7}$$

Subtraction of two single-valued triangular neutrosophic numbers is obtained as Eq. (8):

$$\tilde{a} - \tilde{n} = \langle (a_1 - n_3, a_2 - n_2, a_3 - n_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \rangle. \tag{8}$$

The inverse of a single-valued triangular neutrosophic number $(\tilde{a} \neq 0)$ can be shown as below:

$$\tilde{a}^{-1} = \left\langle \left(\frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}\right); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}} \right\rangle. \tag{9}$$

Multiplication of a single-valued triangular neutrosophic number by a constant value are denoted as follows:

$$\lambda \tilde{a} = \begin{cases} \langle (\lambda a_1, \lambda a_2, \lambda a_3); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}} \rangle \; if \; (\lambda > 0) \\ \langle (\lambda a_3, \lambda a_2, \lambda a_1); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}} \rangle \; if \; (\lambda < 0) \end{cases}. \tag{10}$$

Division of a single-valued triangular neutrosophic number by a constant value are represented as Eq. (11):

$$\frac{\tilde{a}}{\lambda} = \begin{cases} \left\langle \left(\frac{a_1}{\lambda}, \frac{a_2}{\lambda}, \frac{a_3}{\lambda}\right); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}} \right\rangle \; if \; (\lambda > 0) \\ \left\langle \left(\frac{a_3}{\lambda}, \frac{a_2}{\lambda}, \frac{a_1}{\lambda}\right); \alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}} \right\rangle \; if \; (\lambda < 0) \end{cases}. \tag{11}$$

Multiplication of two single-valued triangular neutrosophic numbers can be shown as follows:

$$\tilde{a} . \tilde{n} = \begin{cases} \langle (b_1 c_1, b_2 c_2, b_3 c_3); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \rangle \; if \; (b_3 > 0, c_3 > 0) \\ \langle (b_1 c_3, b_2 c_2, b_3 c_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \rangle \; if \; (b_3 < 0, c_3 > 0) \\ \langle (b_3 c_3, b_2 c_2, b_1 c_1); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \rangle \; if \; (b_3 < 0, c_3 < 0) \end{cases}. \tag{12}$$

Division of two single-valued triangular neutrosophic numbers can be computed as Eq. (13):

$$\frac{\tilde{a}}{\tilde{n}} = \begin{cases} \left\langle \left(\frac{a_1}{n_3}, \frac{a_2}{n_2}, \frac{a_3}{n_1}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \right\rangle \; if \; (a_3 > 0, n_3 > 0) \\ \left\langle \left(\frac{a_3}{n_3}, \frac{a_2}{n_2}, \frac{a_1}{n_1}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \right\rangle \; if \; (a_3 < 0, n_3 > 0) \\ \left\langle \left(\frac{a_3}{n_1}, \frac{a_2}{n_2}, \frac{a_1}{n_3}\right); \alpha_{\tilde{a}} \wedge \alpha_{\tilde{n}}, \theta_{\tilde{a}} \vee \theta_{\tilde{n}}, \beta_{\tilde{a}} \vee \beta_{\tilde{n}} \right\rangle \; if \; (a_3 < 0, n_3 < 0) \end{cases}. \tag{13}$$

Score function (s_b) for a single-valued triangular neutrosophic number $b=(b_1,b_2,b_3)$ can be obtained as follows [21,22]:

$$s_b = (1 + b_1 - 2 * b_2 - b_3)/2, \tag{14}$$

where $s_b \in [-1,1]$.

The maximum distance $e_{max}(a,b)$ between two single-valued triangular neutrosophic numbers such as $a = (a_1,a_2,a_3)$ and $b = (b_1,b_2,b_3)$ can be calculated as below [21,22]:

$$e_{max}(a,b) = \begin{cases} |a_1 - b_1| & a_1, b_1 \in \Omega_{max} \\ |a_3 - b_3| & a_3, b_3 \in \Omega_{min} \end{cases}. \tag{15}$$

2.3. Neutrosophic AHP

Steps of neutrosophic AHP can be summarized as below [21,22,23]:

1. Decision problem is formed in terms of hierarchical view including goal, criteria, sub-criteria and alternatives, respectively.

2.Neutrosophic evaluation matrix including triangular neutrosophic number is constructed in terms of pairwise comparisons. Neutrosophic pairwise evaluation matrix $(\tilde{O})$ is seen as below:

$$\tilde{O} = \begin{bmatrix} \tilde{1} & \tilde{o}_{12} & \cdots & \tilde{o}_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{o}_{n1} & \tilde{o}_{n2} & \cdots & \tilde{1} \end{bmatrix}. \tag{16}$$

where $\tilde{o}_{ji} = (\tilde{o}_{ij})^{-1}$ is valid for Eq. (16).

3. Neutrosophic pairwise evaluation matrix is obtained via scale seen as Table 1 that shows a set of linguistic variables used by decision makers as well as an importance weight based on neutrosophic values [13,22].

Table 1. Linguistic Terms

Saaty Fundamental Scale	Lingusitic Terms for Importance Levels	Neutrosophic Triangular Set with Reciprocals
1	Equally influential	<(1,1,1);0.5,0.5,0.5>
2	Intermediate value	<(1,2,3); 0.4,0.65,0.6>
3	Slightly influential	<(2,3,4); 0.3,0.75,0.7>
4	Intermediate value	<(3,4,5); 0.6,0.35,0.4>
5	Strongly influential	<(4,5,6); 0.8,0.15,0.2>
6	Intermediate value	<(5,6,7); 0.7,0.25,0.3>
7	Very strongly influential	<(6,7,8); 0.9,0.1,0.1>
8	Intermediate value	<(7,8,9); 0.85,0.1,0.15>
9	Absolutely influential	<(9,9,9); 1,0,0>

4. Neutrosophic pairwise evaluation matrix is transformed into the deterministic pairwise evaluation matrix for computing the weights of criteria as below:

Suppose $\tilde{o}_{ij}$ = <(d_1, e_1, f_1); $\alpha_{\tilde{o}}, \theta_{\tilde{o}}, \beta_{\tilde{o}}$> as a single-valued neutrosophic number, then the score and accuracy degrees for $\tilde{o}_{ij}$ are obtained according to Eqs. (17-18):

$$S(\tilde{o}_{ij}) = \frac{1}{16}[d_1 + e_1 + f_1]x(2 + \alpha_{\tilde{o}} - \theta_{\tilde{o}} - \beta_{\tilde{o}}), \tag{17}$$

$$A(\tilde{o}_{ij}) = \frac{1}{16}[d_1 + e_1 + f_1]x(2 + \alpha_{\tilde{o}} - \theta_{\tilde{o}} + \beta_{\tilde{o}}). \quad (18)$$

The score and accuracy degree of $\tilde{o}_{ij}$ are calculated by using the Eqs. (19-20):

$$S(\tilde{o}_{ji}) = 1/S(\tilde{o}_{ij}), \quad (19)$$

$$A(\tilde{o}_{ji}) = 1/A(\tilde{o}_{ij}). \quad (20)$$

Then the deterministic pairwise evaluation matrix is obtained as below:

$$O = \begin{bmatrix} 1 & o_{12} & \cdots & o_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ o_{n1} & o_{n2} & \cdots & 1 \end{bmatrix}. \quad (21)$$

Ranking of priorities as eigenvector X is handled as follows:

a) Firstly column entries are normalized by dividing each entry to the sum of column

b) Then row averages are summed.

5. Consistency index *(CI)* and consistency ratio *(CR)* values are calculated. If *CR* is greater than 0.1, the process should be repeated due to unreliable decision-makers' judgments.

CI is calculated as below:

a) Each value in the first column of the pairwise evaluation matrix is multiplied by the priority of the first criterion and this process is applied for all columns. Values are summed across the rows in order to obtain the weighted sum vector.

b) The components of the weighted sum vector are divided by corresponding to the priority of each criterion. Then the average of values are handled and shown by λ_{max}.

c) The value of *CI* is obtained according to Eq. (22):

$$CI = \frac{\lambda_{max} - n}{n-1}. \quad (22)$$

The number of components being compared is represented by n.

After finding the value of *CI* as above, *CR* is calculated as Eq. (23):

$$CR = \frac{CI}{RI} \quad (23)$$

where *RI* shows the consistency index for randomly generated pairwise evaluation matrix and seen as Table 2.

Table 2. RI table considered for obtaining CR value

Order of random matrix (n)	**Related RI Value**
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.4
9	1.45
10	1.49

6. Alternatives are ranked according to overall priority values.

3. RESULTS

Nine criteria were evaluated by consulting the opinions of five experts in analysing the barriers related to smart manufacturing systems. Due to the ease of representation, the expert evaluations (DM1,...,DM5) regarding the criteria are expressed in Table 3 by Saaty's Fundamental Scale values.

Table 3. Linguistic Evaluations of Experts

DM1	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	1/5	5	3	1	1/3	1/4	1/3	4
C2	5	1	7	6	3	1/3	3	3	4
C3	1/5	1/7	1	3	1/4	1/3	3	3	2
C4	1/3	1/6	1/3	1	1/6	3	3	1/3	1/4
C5	1	1/3	4	6	1	4	6	5	7
C6	3	3	3	1/3	1/4	1	5	4	5
C7	4	1/3	1/3	1/3	1/6	1/5	1	1/6	1/5
C8	3	1/3	1/3	3	1/5	1/4	6	1	1/3
C9	1/4	1/4	1/2	4	1/7	1/5	5	3	1

DM2	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	1/5	5	3	1/5	1/5	1/5	5	1/3
C2	5	1	5	5	1/5	4	5	5	5
C3	1/5	1/5	1	5	1/5	1/3	1/3	1/3	1/6
C4	1/3	1/5	1/5	1	1/7	1/6	1/4	6	1/3
C5	5	5	5	7	1	6	7	8	8
C6	5	1/4	3	6	1/6	1	3	4	1/3
C7	5	1/5	3	4	1/7	1/3	1	1/3	1/4
C8	1/5	1/5	3	1/6	1/8	1/4	3	1	1/4
C9	3	1/5	6	3	1/8	3	4	4	1

DM3	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	1/5	1/3	1	1/3	1/3	1/5	1/3	3
C2	5	1	6	7	1/3	1/3	1/3	3	6
C3	3	1/6	1	1/3	1/7	1/7	1/7	1/6	1/7
C4	1	1/7	3	1	1/7	1/5	1/3	1/3	1/3
C5	3	3	7	7	1	3	7	5	8
C6	3	3	7	5	1/3	1	4	1/4	1
C7	5	3	7	3	1/7	1/4	1	1	1
C8	3	1/3	6	3	1/5	4	1	1	2
C9	1/3	1/6	7	3	1/8	1	1	1/2	1

DM4	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	1/7	6	5	1/4	1/5	1/4	4	1/3
C2	7	1	7	4	1/4	4	4	4	1
C3	1/6	1/7	1	5	1/7	1/5	1/3	1/2	1/2
C4	1/5	1/4	1/5	1	1/7	1/6	3	2	1/4
C5	4	4	7	7	1	9	5	8	8
C6	5	1/4	5	6	1/9	1	4	4	1/5
C7	4	1/4	3	1/3	1/5	1/4	1	1/2	1/6

C8	1/4	1/4	2	1/2	1/8	1/4	2	1	1/6
C9	3	1	2	4	1/8	5	6	6	1

DM5	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	3	2	1/2	3	1/3	1/3	1/2	3
C2	1/3	1	6	4	3	1/3	1/2	1/6	1/4
C3	1/2	1/6	1	4	2	1/5	1/3	1/5	1/4
C4	2	1/4	1/4	1	2	1	1/2	6	2
C5	1/3	1/3	1/2	1/2	1	4	4	4	4
C6	3	3	5	1	1/4	1	2	3	1/3
C7	3	2	3	2	1/4	1/2	1	1/5	3
C8	2	6	5	1/6	1/4	1/3	5	1	1/4
C9	1/3	4	4	1/2	1/4	3	1/3	4	1

By integrating the experts' assessments and completing other steps, the crisp values are obtained as Table 4.

Table 4. Deterministic Pairwise Evaluation Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1,00	0,41	1,63	0,81	0,62	1,12	0,73	2,00	1,07
C2	2,46	1,00	2,79	2,07	0,68	1,77	1,62	0,79	1,09
C3	0,61	0,36	1,00	1,49	0,40	0,75	1,04	0,84	0,61
C4	1,24	0,48	0,67	1,00	0,33	0,40	0,96	1,62	1,00
C5	1,63	1,46	2,47	3,02	1,00	1,62	2,50	2,57	3,83
C6	0,90	0,56	1,34	2,51	0,62	1,00	0,98	0,98	1,04
C7	1,37	0,62	0,96	1,05	0,40	1,02	1,00	0,76	0,44
C8	0,50	1,27	1,19	0,62	0,39	1,02	1,32	1,00	0,72
C9	0,94	0,91	1,64	1,00	0,26	0,96	2,25	1,39	1,00

Finally, the weight values for the criteria are determined, as shown in Table 5.

Table 5. Weights of criteria

Code	Criteria	Weight	Importance Ranking
C1	The problem of giving up traditional manufacturing methods	0.1002	5
C2	Insufficient technical infrastructure	0.1506	2
C3	Senior management's negative view of smart manufacturing systems	0.0739	9
C4	Unemployment issues that may occur because of the use of smart manufacturing systems	0.0804	8
C5	Smart manufacturing systems costs	0.2126	1
C6	Technology intensive business process planning problem	0.1044	4
C7	Anxiety about smart manufacturing systems (such as cyber-attack)	0.0821	7
C8	The problem of a skilled workforce for smart manufacturing systems	0.0894	6
C9	The presence of sudden stops and malfunctions in smart devices	0.1063	3

As seen in Table 5, the most important barrier related to smart manufacturing systems is “smart manufacturing systems costs”. Also, the importance order of criteria is determined as C5>C2>C9>C6>C1>C8>C7>C4>C3.

4. CONCLUSIONS

Today, new technologies such as smart manufacturing systems are used in almost every industry and are rapidly spreading throughout the world. It is well understood that changes brought about by new technologies have a positive impact on business performance. Simultaneously, it is seen that it increases its competitive power through cost advantage and increases customer satisfaction. However, there are numerous barriers, problems, and difficulties in implementing smart manufacturing systems in businesses. In this context, the barriers to smart manufacturing systems in plastic industry enterprises were identified and evaluated using the Neutrosophic AHP in this study. According to the findings, the most important barrier to smart manufacturing systems is "Smart Manufacturing Systems Cost." Because new technologies, such as smart manufacturing systems, require significant resources when first installed, imposing a significant cost burden on businesses.

However, it is necessary to explain that allocating this resource in the medium and long term will result in much higher returns, as well as to support these systems with business strategies, plans, and programs. Furthermore, it is a fact that this burden will be reduced through publicly supported grants and long-term loans. Another barrier is the "the Lack of Technological Infrastructure." It is true that old technological infrastructure is insufficient, particularly during the transition period of enterprises to new technologies, and eliminating this deficiency is a critical issue in terms of efficiency and productivity. It is obvious that another barrier, "the Existence of Unexpected Situations and Failures in Smart Devices," can be overcome by increasing the level of trained and qualified personnel in the applications of smart production systems in enterprises.

In this context, experts who were thought to be parties to the research subject were interviewed, but due to time constraints, the number could not be increased. In future studies involving more businesses, the results of smart manufacturing systems and efficiency, productivity, and capacity variables can be compared.

In the future, the study can be improved by combining fuzzy logic extensions with other MCDM methods and/or other parametric or non-parametric methods, and an implication can be pointed by comparing the results.

REFERENCES

[1] Banger, G.: *Endüsti 4.0 Ekstra.* Dorlion Publishing, Ankara,2017.

[2] Crnjac, M., Veza, I., Banduka, N.: From Concept to the Introduction of Industry 4.0. *International Journal of Industrial Engineering and Mangement,* 8(1), pp.21-30, 2017.

[3] Choi, S.: Digital Manufacturing in Smart Manufacturing Systems: Contribution, Barriers, and Future Directions. In: Umeda S. et al. (Eds.) *Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth.* APMS, IFIP Advances in Information and Communication Technology. 460,pp. 21-29, 2015.

[4] Duman, A.: *Endüstri 4.0 İle Akıllı Üretimin İşletme Performansı Üzerine Etkisi: Vestel Buzdolabı Fabrikası'nda Bir Uygulama,* Unpublished Master Thesis, Manisa Celal Bayar University Graduate School of Social Sciences, Manisa, 2019.

[5] Duman, A., Kargın, S.: Akıllı Üretimin İşletme Performansına Etkisi: Vaka Analizi Yaklaşımı . *Muhasebe ve Finans İncelemeleri Dergisi*,4(2), pp.91-109, 2021.

[6] EFFRA: *Factories Of The Future, Multi-Annual Roadmap for the Contractual PPP under Horizon 2020.* Publications office of the European Union: Brussels, Belgium, 2013.

[7] Kagermann, H., Helbig, J., Hellinger, A., Wahlster, W.: *Recommendations for İmplementing The Strategic İnitiative INDUSTRIE 4.0: Securing The Future of German Manufacturing Industry,* Final Report of The Industrie 4.0 Working Group, Forschungsunion, 2013.

[8] Kang, H., Lee, J,Y., Choi, S., Kim, H., Park, J. H., Son, J. Y.,Kim, B. H., Noh, S. D.: Smart Manufacturing: Past Research, Present Findings, and Future Directions. *International Journal of Precision Engineering and Manufacturing – Green Technology.* 3(1), pp.111-128, 2016.

[9] Korucuk, S.: Üretim İşletmelerinde Verimliliğin Önündeki Engellerin Ve Verim Artırıcı Tekniklerin Bütünleşik Ahp-Topsıs İle Sıralanması: Erzurum İli Örneği. *Verimlilik Dergisi*, (1), pp.219-224, 2019.

[10] Lu, Y., Morris, K.C., Frechette, S.: *Current Standards Landscape for Smart Manufacturing Systems*, National Institute of Standards and Technology,2016.

[11] Öncül, M., Ateş, V.: İşletmelerin Akıllı Üretim Modeline Geçiş Sürecinde Karşılaştıkları Sorunların Belirlenmesi. *Organizasyon ve Yönetim Bilimleri Dergisi*, 12(2), pp.116-132, 2020.

[12] Prokopenko, J.: Verimlilik Yönetimi Uygulamalı Elkitabı (Trans. O. Baykal, N. Atalay ve E. Fidan), National Productivity Center Publishing, No: 476, pp. 1- 315, 2011.

[13] Radwan, N. M., Senousy, M. B., Alaa El Din, M. R.: Neutrosophic AHP multi criteria decision making method applied on the selection of learning management system. Infinite Study, 2016.

[14] Sağbaş, A., Özdil, H.: Konfeksiyon İşletmelerinde Endüstri 4.0 Perspektifinde Akıllı Üretim Sistemleri Entegrasyonu İçin Bir Model Önerisi. *Düzce Üniversitesi Bilim ve Teknoloji Dergisi* , 10 (1) , pp. 434-447, 2022.

[15] Wiktorsson, M., Noh, S. D., Bellgran, M., Hanson, L.: Smart Factories: South Korean and Swedish Examples on Manufacturing Settings. *Procedia Manufacturing,* 25, pp. 471-478, 2018.

[16] Frank, A.G., Dalenogare, L.S., Ayala, N.F.:Industry 4.0. Technologies: Implementation Patterns in Manufacturing Companies. *Int.J.Prod.Econ.*, 210, pp. 15-26, 2019.

[17] Mondal, K., Pramanik, S., Smarandache, F.: Several Trigonometric Hamming Similarity Measures of Rough Neutrosophic Sets and their Applications in Decision Making, In *New Trends in Neutrosophic Theory and Applications*, F. Smarandache and S. Pramanik (Eds.), pp.93-103, Pons Publishing House, Brussels, 2016.

[18] Smarandache, F.: *Neutrosophy:Neutrosophic Probability, Set, and Logic: Analytic Synthesis & Synthetic Analysis,* American Research Press, 1998.

[19] Biswas, P., Pramanik, S., Giri, B.C.: Some Distance Measures of Single Valued Neutrosophic Hesitant Fuzzy Sets and Their Applications to Multiple Attribute Decision Making, In *New Trends in Neutrosophic Theory and Applications,* F. Smarandache and S. Pramanik (Eds.), pp.27-34, Pons Publishing House, Brussels, 2016.

[20] Abdel-Basset, M., Mohamed, M., Zhou, Y., Hezam, I.: Multi-criteria group decision making based on neutrosophic analytic hierarchy process, *Journal of Intelligent & Fuzzy Systems,* 33(6), pp. 4055-4066, 2017.

[21] Stanujkic, D., Zavadskas, E.K., Smarandache, F., Brauers, W.K.M., Karabasevic, D.: A Neutrosophic Extension of the Multimoora Method, *Informatica,* 28(1), pp. 181-192, 2017.

[22] Karamaşa, Ç., Karabasevic, D., Stanujkic, D., Kookhdan, A.R., Mishra, A.R., Ertürk, M.: An Extended Single-Valued Neutrosophic AHP and MULTIMOORA Method to Evaluate the Optimal

Training Aircraft for Flight Training Organizations. *Facta Universitatis Series: Mechanical Engineering,* 19(3), pp.555-578, 2021.
[23] Abdel-Basset, M., Mohamed, M., Smarandache, F.: An extension of neutrosophic AHP-SWOT analysis for strategic planning and decision making, *Symmetry,* 10(4), 116, 2018.
[24] Wang, H., Smarandache, F., Zhang, Y.Q., Sunderraman, R.: Single valued neutrosophic sets, *Multispace and Multistructure,* 4, pp. 410-413, 2010.

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OPTIMAL PREDICTORS BY ADAPTIVE NEURO FUZZY LOGIC FOR ABLATION DEPTH IN MICROMACHINING BY EXCIMER LASER

Miloš MILOVANČEVIĆ
Dalibor PETKOVIĆ

Abstract: *To fabricate multimode polymer waveguides ablation by excimer laser is the most suitable process. However, there is challenging task to control topology of the waveguides which could be time consuming process. In order to overcome the difficulties, it is suitable to establish a predictive approach to obtain optimal parameter for the best topology of the waveguides. In this paper was established a predictive approach by adaptive neuro fuzzy inference system (ANFIS) to determine the impact of fluence, scanning speed, number of shots, number of passes and pulse repetition rate on the mean depth of ablation. Since the depth of ablation affects total internal reflection and insertion loss there is need to analyze the depth in the comprehensive approach. It was found that the number of shots and scanning speed in combination is the most important for the mean depth of ablation. The results could be useful for laser ablation optimization in order to reduce the cost of the process.*

Keywords: *laser; predictors; ablation; micromachining; ANFIS*

1. INTRODUCTION

Recently consumer electronics have challenge to overcome high frequency transmission problems where high interconnectivity plays large portion of the problem. In order to add more features or application miniaturization plays important role where copper transmissions in the electronic circuits exposed the limitations. To solve the issue optical printed circuit is a potential solution since the optical fiber has been used for long haul communications. Since polymer waveguides have been used for the optical interconnections in this study was analyzed laser ablation approach as the proven approach for the printed circuits.

Ablation rate variations between surface and bulk layers indicated changes of the ablation mechanisms across the depth profiles of the films [1]. The levels of precision and accuracy obtainable by laser ablation of zircons in real-world situations using a 193-nm ArF excimer laser coupled to a Nu Plasma MC-ICPMS has been examined in article [2] where the long-term (9 months) levels of precision and accuracy obtained in these standards by laser ablation are ±90. Scan sequence might cause systematic substructures at the surface of the ablated material depending on the overlapping factor [3]. Carbon plasmas produced by laser ablation can have important applications in the synthesis of nanostructured materials of high current interest (nanotubes, nanowires, graphene) or the deposition of diamond-like thin films [4]. Ablation threshold and effective optical penetration depth values are dependent on the wavelength of laser beam (photon energy) and the pulse width [5]. The limit of detection (LOD), ICP mass load effect, downhole induced fractionation and matrix effect of 193 nm ArF excimer laser ablation system at high spatial resolution were systematically investigated [6]. The correction of presbyopia by micromonovision and aspheric aberration ablation with an excimer laser led to minimal changes in stereopsis, contrast sensitivity, and optical quality [7]. The optimal fluence for the ablation of the material has been determined in article [8]. The ablation treatment of a sintered hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) sample has been studied by irradiating the excimer laser in air at one atmosphere for the micro machining treatment [9]. Micromachining and other processing of different materials using lasers have been the focus of a large number of investigations in recent years [10].

Since to control topology of the waveguides could be time consuming and challenging process in this study was applied a predictive approach to obtain optimal parameter for the best topology of the waveguides. The predictive approach was based by adaptive neuro fuzzy inference system (ANFIS) [11] to determine the impact of fluence, scanning speed, number of shots, number of passes and pulse repetition rat on the mean depth of ablation. Since the depth of ablation affects total internal reflection and insertion loss there is need to analyze the depth in the comprehensive approach.

2. METHODOLOGY AND MATERIALS

2.1. Experimental procedure

Figure 1 shows schematic overview of different types of ablation depths by laser beam. Minimum depth of ablation is desirable for the long-distance transmission of signal through the polymeric waveguides. However, there is no desirable to decrease depth of ablation too much since cladding could be exposed which leads to the undesired thermal effects.

Data samples for ANFIS processing are collected and arranged from literature [12]. Table 1 shows input and output data samples. The used inputs are: fluence, scanning speed, number of shots, number of passes and pulse repetition rate. The output represents the mean depth of laser ablation.

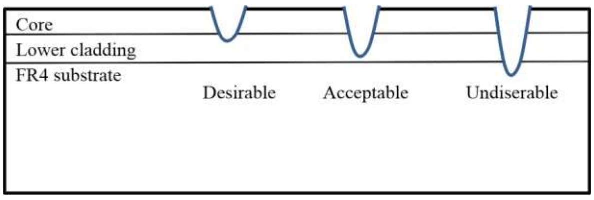

Fig.1. Schematic overview of different types of ablation depths by laser beam

Table 1. Input and output data samples for the laser ablation process

In1	In2	In3	In4	In5	Output
Number of shots	Fluence (J/cm2)	Scanning speed (mm/min)	Pulse repetition rate (Hz)	Number of passes	Mean depth (μm)/1 shot
1	0.086	120	20	1	0.678
2	0.086	60	20	1	1.65
3	0.086	40	20	1	2.49
4	0.086	30	20	1	3.12
5	0.086	24	20	1	4.04
6	0.086	20	20	1	5.15
7	0.086	17.1	20	1	5.53
8	0.086	15	20	1	6.2
9	0.086	13.3	20	1	6.61
10	0.086	12	20	1	7.63
12	0.086	10	20	1	8.5
14	0.086	8.57	20	1	10.4
16	0.086	7.5	20	1	11.4
18	0.086	6.67	20	1	13.1
20	0.086	6	20	1	14.5
22	0.086	5.45	20	1	17
24	0.086	5	20	1	17.5
26	0.086	4.62	20	1	18.9
28	0.086	4.29	20	1	20.2
30	0.086	4	20	1	21
10	0.03	6	10	1	0.173
10	0.058	6	10	1	0.425
10	0.086	6	10	1	0.695
10	0.113	6	10	1	0.988
10	0.141	6	10	1	1.35
10	0.169	6	10	1	1.66
10	0.197	6	10	1	1.82
10	0.224	6	10	1	2.04
10	0.252	6	10	1	2.17
10	0.28	6	10	1	2.36
1	0.086	120	20	3	2.43
1	0.086	120	20	4	3.1
1	0.086	120	20	5	3.42
1	0.086	120	20	9	7.58
1	0.086	120	20	10	8.47
1	0.086	72	12	1	0.967

2.2. ANFIS methodology

ANFIS network has five layers as it shown in Figure 2. The main core of the ANFIS network is fuzzy inference system. Layer 1 receives the inputs and convert them in the fuzzy value by membership functions. In this study bell shaped membership function is used since the function has the highest capability for the regression of the nonlinear data.

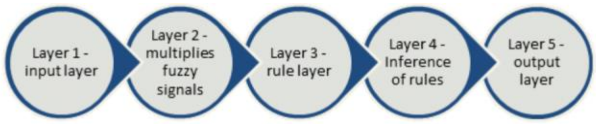

Fig.2. ANFIS layers

Bell-shaped membership functios is defined as follows:

$$\mu(x) = bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i}\right)^2\right]^{b^i}} \tag{1}$$

where $\{a_i, b_i, c_i\}$ is the parameters set and x is input.

Second layer multiplies the fuzzy signals from the first layer and provides the firing strength of as rule. The third layer is the rule layers where all signals from the second layer are normalized. The fourht layer provides the inference of rules and all signals are converted in crisp values. The final layers sumarized the all signals and provied the output crisp value.

3. RESULTS

ANFIS methodology was used for selection of the optimal predictors for mean ablation depth of the excimer laser micromachining. The selection is important as preprocessing of the input parameters to remove the inputs with small relevance. The data set is arranged from the data file in Table 1. The dataset is then partitioned into a training set (odd-indexed samples) and a checking set (even-indexed samples) by following command in MATLAB Software:

```
>>[data] = ablation;
>>trn_data = data(1:2:end,:);
>>chk_data = data(2:2:end,:);
```

The function "exhsrch" performs an exhaustive search within the available inputs to select the set of inputs that most influence the mean ablation depth of the excimer laser micromachining. The first parameter to the function specifies the number if input combinations to be tried during the selection procedure. Essentially, "exhsrch" builds an ANFIS model for each combination and trains it for one epoch and reports the performance achieved. The following command line is used for determine the one most influential attribute in predicting the output:

```
>> exhsrch(1,trn_data,chk_data);
```

The following results are obtained (Figure 3):

ANFIS model 1: in1 --> trn=2.3286, chk=2.2643
ANFIS model 2: in2 --> trn=5.3778, chk=5.9980
ANFIS model 3: in3 --> trn=5.5097, chk=7.5030
ANFIS model 4: in4 --> trn=5.0303, chk=5.2646
ANFIS model 5: in5 --> trn=5.7667, chk=6.3873

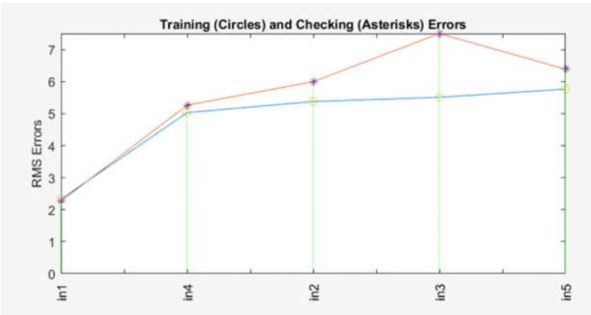

Fig.3. Predictors' influence on the mean ablation depth of the excimer laser micromachining

The lest-most input variable (number of shots – in1) in Figure 3 has the least error or in other words the most relevance with respect to the output. Thae plot and results from the function clearly indicate that the input attribute "number of shots" is the most influential. The training and checking errors are comparable, which implies that there is no overfitting. This means we can push a little further and explore if we can select more than one input attribute to build the ANFIS model.
Intuitively, one can simply select "number of shots" and "pulse repetition rate" directly since they have the least errors as shown in the Figure 3. However, this will not necessarily be the optimal combination of two inputs that results in the minimal training error. To verify this, one can use:

```
>> exhsrch(2,trn_data,chk_data);
```

The following results are obtained (Figure 4):

ANFIS model 1: in1 in2 --> trn=1.9985, chk=2.0600
ANFIS model 2: in1 in3 --> trn=1.4188, chk=2.5107
ANFIS model 3: in1 in4 --> trn=1.4884, chk=1.2542
ANFIS model 4: in1 in5 --> trn=1.9776, chk=2.0096
ANFIS model 5: in2 in3 --> trn=4.0108, chk=13.2769
ANFIS model 6: in2 in4 --> trn=5.0156, chk=5.2467
ANFIS model 7: in2 in5 --> trn=5.1248, chk=5.9065
ANFIS model 8: in3 in4 --> trn=2.0209, chk=9.9226
ANFIS model 9: in3 in5 --> trn=5.3377, chk=7.3694
ANFIS model 10: in4 in5 --> trn=4.6570, chk=4.9967

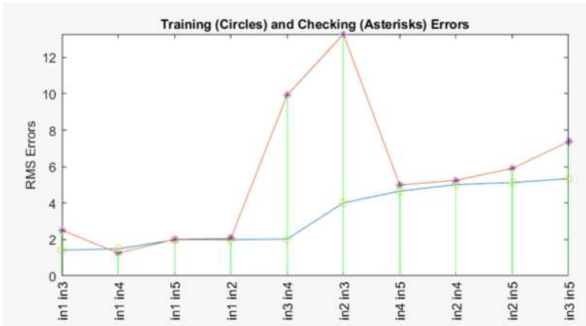

Fig.4. All two predictors combinations influence on the mean ablation depth of the excimer laser micromachining

The results from "exhsrch" indicate that "number of shots" and "scanning speed" form the optimal combination of two input attributes or two predictors. The training and checking errors are getting distinguished which indicate the outset of overfitting. It may be not preferable to use more than two input for building the ANFIS model. However, one can confirm the premise to verify it's validity by following command line:

```
>> exhsrch(3,trn_data,chk_data);
```

The following results are obtained (Figure 5):

ANFIS model 1: in1 in2 in3 --> trn=1.3660, chk=2.5504
ANFIS model 2: in1 in2 in4 --> trn=1.4381, chk=1.1918
ANFIS model 3: in1 in2 in5 --> trn=1.5072, chk=1.7363
ANFIS model 4: in1 in3 in4 --> trn=1.4187, chk=1.1824
ANFIS model 5: in1 in3 in5 --> trn=0.3849, chk=2.4289
ANFIS model 6: in1 in4 in5 --> trn=0.4080, chk=0.5736
ANFIS model 7: in2 in3 in4 --> trn=1.9842, chk=9.9687
ANFIS model 8: in2 in3 in5 --> trn=3.7711, chk=13.1247
ANFIS model 9: in2 in4 in5 --> trn=4.6412, chk=4.9779
ANFIS model 10: in3 in4 in5 --> trn=1.4896, chk=9.8524

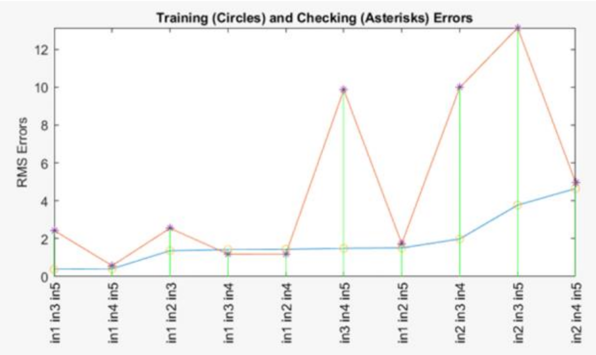

Fig.5. All three predictors combinations influence on the mean ablation depth of the excimer laser micromachining

The Figure 5 shows the results of selecting three predictors, in which "number of shots", "scanning speed" and "number of passes" are selected as the best combination of three predictors. However, the minimal training and checking error do not reduce significantly from that of the best two predictors model, which indicates that the newly added predictor does not improve the prediction much. For better generalization it is preferable to pick a model with simple structure. For further analysis model with two predictors will be extracted.

The function "exhsrch" only trains each of the ANFIS model for a single epoch to be able to quickly select the optimal input attributes. In the next step, after extraction of the two optimal predictors, 100 epochs are used for training the new ANFIS model. Figure 6 shows error curve for 100 epochs of the ANFIS training for two predictors. The green curve presents the training errors and the red curve presents the checking errors. The minimal checking error occurs at the epoch 24th, which is indicated by a circle. Notice that the checking error curve is raising after epoch 24th, indicating that further training over fitch the data and produces worse generalization.

Fig.6. Training and checking errors for two optimal predictors

Figure 7 shows input/output surface of the ANFIS model at the minimal checking error during the training process. The surface shown in the figure 7 is a nonlinear and monotonic surface and illustrates how the ANFIS model will respond to varying values of initial strength and exposure age.

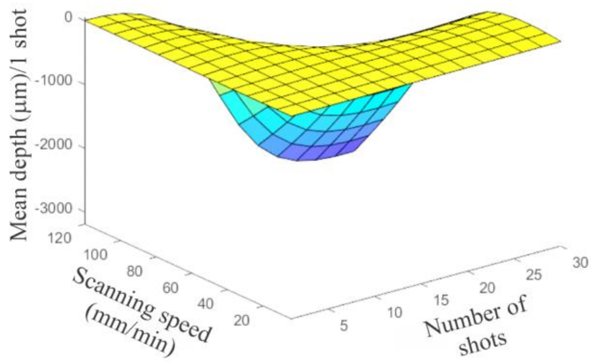

Fig.7. Input/output surface for trained ANFIS model

In the Figure 7 one can see some spurious effects since the surface goes under zero which is not acceptable. This is a direct result from lack of data. Figure 8 shows data distribution for the selected input pairs where one can see the lack of training and checking data at the upper right corner cased the spurious ANFIS surface.

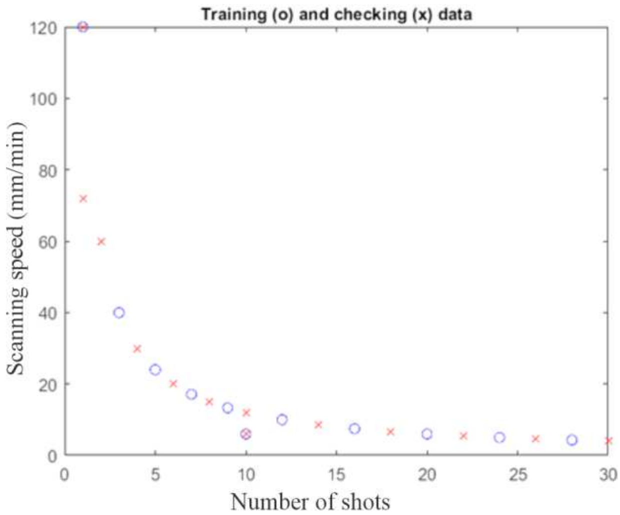

Fig.8. Data distribution for the selected input pair

4. CONCLUSION

Since polymer waveguides have been used for the optical interconnections in this study was analyzed laser ablation approach as the proven approach for the printed circuits. Controlling of topology of the waveguides could be challenging task there is need to estimate the optimal parameters of the process. which could be time consuming process. In this study was established a predictive approach to obtain optimal parameter for the best topology of the waveguides. Adaptive neuro fuzzy inference system (ANFIS) was used to determine the impact of fluence, scanning speed, number of shots, number of passes and pulse repetition rate on the mean depth of ablation. It was found that the number of shots and scanning speed in combination is the most important for the mean depth of ablation. The results could be useful for laser ablation optimization in order to reduce the cost of the process.

DECLARATION

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REFERENCES

[1] Theodorakopoulos, C., & Zafiropulos, V. (2009). Depth-profile investigations of triterpenoid varnishes by KrF excimer laser ablation and laser-induced breakdown spectroscopy. *Applied surface science*, *255*(20), 8520-8526.

[2] Woodhead, J., Hergt, J., Shelley, M., Eggins, S., & Kemp, R. (2004). Zircon Hf-isotope analysis with an excimer laser, depth profiling, ablation of complex geometries, and concomitant age estimation. *Chemical Geology*, *209*(1-2), 121-135.

[3] Mrochen, M., Schelling, U., Wuellner, C., & Donitzky, C. (2009). Influence of spatial and temporal spot distribution on the ocular surface quality and maximum ablation depth after photoablation with a 1050 Hz excimer laser system. *Journal of Cataract & Refractive Surgery*, *35*(2), 363-373.

[4] Ursu, C., Nica, P., & Focsa, C. (2018). Excimer laser ablation of graphite: The enhancement of carbon dimer formation. *Applied Surface Science*, *456*, 717-725.

[5] See, T. L., Liu, Z., Li, L., & Zhong, X. L. (2016). A comparison of the characteristics of excimer and femtosecond laser ablation of acrylonitrile butadiene styrene (ABS). *Applied Surface Science*, *364*, 467-476.

[6] Wu, S. T., Wang, Y. P., Xu, C. X., & YUAN, J. H. (2016). Elemental fractionation studies of 193 nm ArF excimer laser ablation system at high spatial resolution mode. *Chinese Journal of Analytical Chemistry*, *44*(7).

[7] Romero, M., Castillo, A., Carmona, D., & Palomino, C. (2019). Visual quality after presbyopia correction with excimer laser ablation using micromonovision and modulation of spherical aberration. *Journal of Cataract & Refractive Surgery*, *45*(4), 457-464.

[8] Schaefer, M., Holtkamp, J., & Gillner, A. (2011). Ablation of PEDOT/PSS with excimer lasers for micro structuring of organic electronic devices. *Synthetic Metals*, *161*(11-12), 1051-1057.

[9] Nakata, K., Umehara, M., & Tsumura, T. (2007). Excimer laser ablation of sintered hydroxyapatite. *Surface and Coatings Technology*, *201*(9-11), 4943-4947.

[10] Shaheen, M. E., Gagnon, J. E., & Fryer, B. J. (2019). Studies on laser ablation of silicon using near IR picosecond and deep UV nanosecond lasers. *Optics and Lasers in Engineering*, *119*, 18-25.

[11] Jang, J.-S.R, *ANFIS: Adaptive-Network-based Fuzzy Inference Systems*, IEEE Trans. On Systems, Man, and Cybernetics (1993), Vol.23, 665-685.

[12] Tamrin, K. F., Zakariyah, S. S., Hossain, K. M. A., & Sheikh, N. A. (2018). Experiment and prediction of ablation depth in excimer laser micromachining of optical polymer waveguides. *Advances in Materials Science and Engineering*, *2018*.

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ADAPTIVE NEURO-FUZZY ESTIMATION OF COMPRESSIVE STRENGTH OF HOLLOW CONCRETE MASONRY PRISMS

Dalibor PETKOVIĆ
Miloš MILOVANČEVIĆ

Abstract: *The main aim of the study was to analyze the effects of height-thickness ratio of prisms, compressive strength of hollow concrete blocks and compressive strength of hollow concrete mortars on the compressive strength of hollow concrete block masonry prisms. In order to analyze the parameters effect on the compressive strength of hollow concrete block masonry prisms adaptive neuro fuzzy inference system (ANFIS) was used as a type of soft computing approach which is suitable for nonlinear data samples. The data samples were acquired from literature review. The data samples were loaded in ANFIS toolbox in MATLAB software and corresponding results were observed. Obtained results shown high influence of compressive strength of hollow concrete blocks on the compressive strength of hollow concrete block masonry prisms. The results showed the high predictive accuracy according to the suggested data pairs.*

Keywords: *concrete; compressive strength; concrete masonry prism; ANFIS*

1. INTRODUCTION

Compressive strength of hollow concrete block masonry could be considered as one of the most important mechanical parameter in design of masonry structures. This parameter has significant impact on the structure safety and economic assessment as well. Estimation of the parameters is challenging task because of complex behavior of the structure since there are different components like hollow concrete blocks and mortars which caused different behavior.
A set of non-linear mathematical expressions to calculate the compressive strength and the elastic modulus of masonry prisms with hollow concrete blocks were obtained in paper [1] and results showed that the compressive and tensile strength of the hollow concrete block and the mortar thickness are the most influential parameters for the maximum compressive strength. An experimental study was conducted in paper [2] to study the effect of mortar strength on the uniaxial compressive strength characteristics of masonry prisms constructed with low-strength hollow concrete blocks where it was observed that the use of higher strength mortar does not have a marked effect on the prism strength of low-strength hollow concrete blocks masonry prisms. Masonry prisms constructed with non-shrink grout showed, on average, an increase in the compressive strength when compared to masonry prisms constructed with regular grout [3]. Grouted prisms constructed with grouts without the shrinkage-compensating admixture were, on average, less efficient than hollow prisms [4]. The bond strength of the alkali-activated slag concrete hollow block (AASCHB) masonry was found to be directly related to the compressive strength of the alkali-activated slag (AAS) mortar, where higher compressive strength led to higher bond strength [5]. The impacts of joint thickness are significantly greater in elements constructed with high-strength blocks [6]. Prisms were produced with blocks and grouts with different strength levels, and mortars with strength of 70% of the blocks' net area strength [7]. In paper [8] has been highlighted the necessity for improving the prediction of compressive strength of concrete masonry by masonry design codes.
Artificial neural networks represent one of the most popular approach for modeling and simulation of different systems and processes. These is because since the artificial neural networks have parallel architectures for solving of difficult and highly nonlinear problems. Therefore the main aim of the study is to apply artificial neural network merged with fuzzy logic controller for estimation of parameters influence on the compressive strength of hollow concrete block masonry prisms. Furthermore the selected parameters are used for prediction of the compressive strength of hollow concrete block masonry prisms. Adaptive neuro fuzzy inference system (ANFIS) [9] is used as a type of artificial neural network which is suitable for nonlinear data samples. The data samples include 102 different samples which were acquired from literature review. Each of the samples have different curing days. The data samples were loaded in

ANFIS toolbox in MATLAB software and corresponding results were observed.

2. METHODOLOGY AND MATERIALS

2.1. Experimental procedure

Considering the influence of the height-to-thickness ratio (h/t), unit compressive strength (fb), and mortar compressive strength (fm) of the prisms on their compressive strength (f), two types of masonry prisms having six different block/mortar combinations were prepared in this study. The input and output values of the data samples are presented in Table 1 according to the investigation in article [10].

Table 1. Input and output data samples [10]

Input 1: fb (MPa)	**Input 2:** fm (MPa)	**Input 3:** h/t	**Output:** fm (MPa)
27.2	17.5	2.8	24.67
40.5	17.5	2.8	27
24.6	17.5	2.8	20.75
24.6	10.4	2.8	18.2
24.6	4.6	2.8	17.7
23	17.5	4.3	21.15
15.9	17.5	3.9	14.9
21.2	17.5	3.9	16.75
18.1	17.5	1.8	14.25
17.2	22.8	4.2	13.93
17.2	14.8	4.2	13.8
26.1	22.8	4.2	20.69
26.1	14.8	4.2	19.79
15.4	22.8	2.7	11.66
15.4	14.8	2.7	11.31
23.8	22.8	2.7	18.82
23.8	14.8	2.7	20.76
15.6	22.8	2	13.45
15.6	14.8	2	14.82
27.7	22.8	2	22
27.7	14.8	2	22.69
19.7	15.1	4.2	15.8
19.7	16.7	4.2	16
19.7	17.2	4.2	15.93
19.7	5.7	4.2	15.38
19.7	14.7	4.2	16.4
19.7	18.2	4.2	16.28
32.2	14.2	4.2	25.41
22	14.2	4.2	18
21.3	14.2	4.2	19.38
20.2	14.2	4.2	17.86
20	14.2	4.2	16.14
15.6	14.2	4.2	12.76
20	15.4	3.1	17.4
25.7	20.2	3.1	24.2
20	9.2	3.1	17.8
20	21.2	3.1	21.25
25.7	15.4	3.1	20.6
25.7	26.5	3.1	25.5
20	21.2	2.1	24.9
20	26.5	3.1	21.4
25.7	21.2	2.1	26
19.8	15.6	2.9	13.9
19.8	12.2	2.9	13.22
19.8	5	2.9	11.89
19.8	4.3	2.9	10.82
17.6	15.6	2.9	13.76
17.6	12.3	2.9	11.14
17.6	5	2.9	10.14
17.6	4.3	2.9	9.75
13.5	12.2	2.9	9.1
13.5	5	2.9	8.74
13.5	4.3	2.9	8.39
10.9	5	2.9	7.24
10.9	4.3	2.9	6.63
9	4.9	4.2	7.11
13.4	4.9	4.2	9.2
14.1	9.1	2	17
14.1	14	2	15.8
20.8	9.1	2	23
17.7	9.1	2	18.6
23.3	9.1	2	20.5
28.3	9.1	2	23.5
31.1	9.1	2	23.8
35	9.1	2	23.7
38	9.1	2	29.2
14.1	4.6	2	15.2
17.7	4.6	2	17.5
20.8	4.6	2	20.6
23.3	4.6	2	17.3
28.3	4.6	2	22.3
31.1	4.6	2	21
35	4.6	2	21.5
38	4.6	2	24.4
14.1	10.8	2	14.7
23.3	10.8	2	20.8
38	10.8	2	27.5
14.1	3.9	2	13.7
23.3	3.9	2	15.6
38	3.9	2	24.2
23.3	14	2	20.9
38	14	2	31
14.1	6.7	2	15.4
23.3	6.7	2	17.2
38	6.7	2	28.1
35.1	22.8	3	24.2
35.1	22.8	2	25.7
25.9	14.9	2.1	19.24
13.9	10.5	3.1	11.74
13.9	10.5	3.1	10.08

2.2. ANFIS methodology

ANFIS network has five layers as it shown in Figure 1. The main core of the ANFIS network is fuzzy inference system. Layer 1 receives the inputs and convert them in the fuzzy value by membership functions. In this study bell shaped membership function is used since the function has the highest capability for the regression of the nonlinear data.

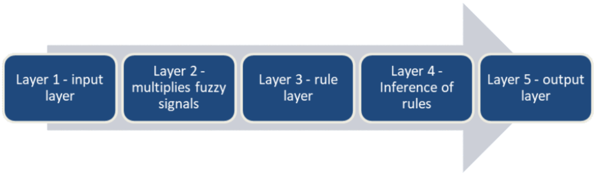


Fig.1. ANFIS layers

Bell-shaped membership functios is defined as follows:

$$\mu(x) = bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i}\right)^2\right]^{b^i}} \quad (1)$$

where $\{a_i, b_i, c_i\}$ is the parameters set and x is input.

Second layer multiplies the fuzzy signals from the first layer and provides the firing strength of as rule. The third layer is the rule layers where all signals from the second layer are normalized. The fourht layer provides the inference of rules and all signals are converted in crisp values. The final layers sumarized the all signals and provied the output crisp value.

3. RESULTS

3.1. Accuracy indices

Performances of the proposed models are presented as root means square error (RMSE), Coefficient of determination (R^2) and Pearson coefficient (r) as follows:

1) RMSE

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \quad (2)$$

2) Pearson correlation coefficient (r)

$$r = \frac{n\left(\sum_{i=1}^{n} O_i \cdot P_i\right) - \left(\sum_{i=1}^{n} O_i\right) \cdot \left(\sum_{i=1}^{n} P_i\right)}{\sqrt{\left(n\sum_{i=1}^{n} O_i^2 - \left(\sum_{i=1}^{n} O_i\right)^2\right) \cdot \left(n\sum_{i=1}^{n} P_i^2 - \left(\sum_{i=1}^{n} P_i\right)^2\right)}} \quad (3)$$

3) Coefficient of determination (R^2)

$$R^2 = \frac{\left[\sum_{i=1}^{n} (O_i - \overline{O_i}) \cdot (P_i - \overline{P_i})\right]^2}{\sum_{i=1}^{n} (O_i - \overline{O_i}) \cdot \sum_{i=1}^{n} (P_i - \overline{P_i})} \quad (4)$$

where P_i and O_i are known as the experimental and forecast values, respectively, and n is the total number of dataset.

3.2. Feature selection

ANFIS methodology was used for feature selection of the compressive strength of hollow concrete block masonry prisms prediction. The feature selection is important as preprocessing of the input parameters in order to remove unnecessary inputs. Data samples are divided in two groups for analyzing purpose. 50% data is used for training and remaining 50% is used for checking purpose of the ANFIS network. ANFIS network is trained based on input and output pairs in Table 1.

Figure 2 shows the compressive strength of hollow concrete block masonry prism relevance with the single inputs. The input with the smallest training error has the strongest relevance with the compressive strength of hollow concrete block masonry prism prediction. As can be seen in Figure 2 the unit compressive strength (input 1) has the strongest relevance with the compressive strength of hollow concrete block masonry prism prediction.

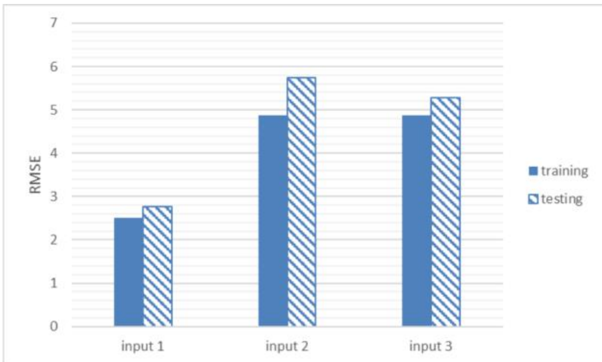


Fig.2. Effects of single parameter on the compressive strength of hollow concrete block masonry prisms

Furthermore one can combine two or three input factors in order to find the optimal combinations for the compressive strength of hollow concrete block masonry prisms prediction. Figure 3 shows ANFIS models for optimal combination of two input factors for the compressive strength of hollow concrete block masonry prisms prediction. As can be seen the combination of unit compressive strength (input 1) and height-to-thickness ratio (input 3) is the optimal combination of two input factors for the compressive strength of hollow concrete block masonry prisms prediction.

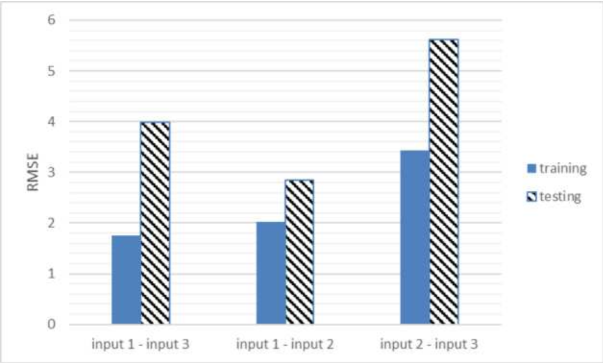
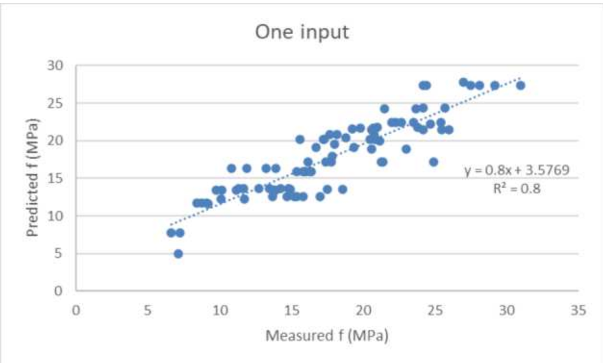


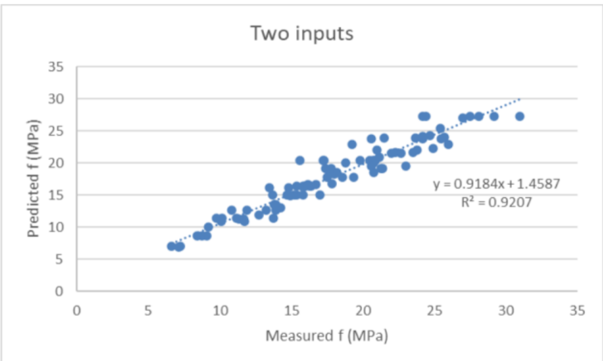
Fig.3. Effects of two parameters on the compressive strength of hollow concrete block masonry prisms

3.3. ANFIS prediction

Figure 4 show ANFIS prediction of the compressive strength of hollow concrete block masonry prisms based on selected features. Based on the coefficient of determination the ANFIS prediction with two features has the highest accuracy. However the ANFIS prediction with one feature has medium accuracy. Table 2 shows ANFIS prediction results of the compressive strength of hollow concrete block masonry prisms based on the three statistical indicators.



(a)



(b)

Fig.4. ANFIS prediction of compressive strength of hollow concrete block masonry prism based on selected input combinations: (a) one feature, (b) two features

Table 2. Statistical indicator for the prediction of compressive strength of hollow concrete block masonry prism

	Input 1	**Input 1 Input 3**
r	0.8944	0.9595
R^2	0.8	0.9207
RMSE	2.4764	1.5594

4. CONCLUSION

In this study was analyzed effect of effects of height-thickness ratio of prisms, compressive strength of hollow concrete blocks and compressive strength of hollow concrete mortars on the compressive strength of hollow concrete block masonry prisms by adaptive neuro fuzzy inference system (ANFIS). The main concluding remarks were:

- There is high influence of unit compressive strength on the compressive strength of hollow concrete block masonry prism.
- Combination of unit compressive strength and height-to-thickness ratio is the optimal combination of two parameters for the prediction of the compressive strength of hollow concrete block masonry prism.

The results showed the high predictive accuracy according to the suggested data pairs.

DECLARATION

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REFERENCES

[1] Álvarez-Pérez, J., Chávez-Gómez, J. H., Terán-Torres, B. T., Mesa-Lavista, M., & Balandrano-Vázquez, R. (2020). Multifactorial behavior of the elastic modulus and compressive strength in masonry prisms of hollow concrete blocks. Construction and Building Materials, 241, 118002.

[2] Syiemiong, H., & Marthong, C. (2020). Effect of mortar grade on the uniaxial compression strength of low-strength hollow concrete block masonry prisms. Materials Today: Proceedings.

[3] AbdelRahman, B., & Galal, K. (2020). Influence of pre-wetting, non-shrink grout, and scaling on the compressive strength of grouted concrete masonry prisms. Construction and Building Materials, 241, 117985.

[4] Fonseca, F. S., Fortes, E. S., Parsekian, G. A., & Camacho, J. S. (2019). Compressive strength of high-strength concrete masonry grouted prisms. Construction and Building Materials, 202, 861-876.

[5] Jiao, Z., Wang, Y., Zheng, W., Huang, W., & Zhao, Y. (2019). Bond properties of alkali-activated slag concrete hollow block masonry with different mortar strength grades. Construction and Building Materials, 216, 149-165.

[6] Caldeira, F. E., Nalon, G. H., de Oliveira, D. S., Pedroti, L. G., Ribeiro, J. C. L., Ferreira, F. A., & de Carvalho, J. M. F. (2020). Influence of joint thickness and strength of mortars on the compressive behavior of prisms made of normal and high-strength concrete blocks. Construction and Building Materials, 234, 117419.

[7] Martins, R. O. G., Nalon, G. H., Sant'Ana, R. D. C. S., Pedroti, L. G., & Ribeiro, J. C. L. (2018). Influence of blocks and grout on compressive strength and stiffness of concrete masonry prisms. Construction and Building Materials, 182, 233-241.

[8] Sarhat, S. R., & Sherwood, E. G. (2014). The prediction of compressive strength of ungrouted hollow concrete block masonry. Construction and Building Materials, 58, 111-121.

[9] Jang, J.-S.R, ANFIS: Adaptive-Network-based Fuzzy Inference Systems, IEEE Trans. On Systems, Man, and Cybernetics (1993), Vol.23, 665-685.

[10] Zhou, Q., Wang, F., & Zhu, F. (2016). Estimation of compressive strength of hollow concrete masonry prisms using artificial neural networks and adaptive neuro-fuzzy inference systems. Construction and Building Materials, 125, 417-426.

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GREEN BUILDING TECHNOLOGIES FOR SUSTAINABLE FUTURE

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Abstract: *The growing world energy needs in the last years have raised concerns over energy supply, exhaustion of energy resources and heavy environmental impacts such as global warming and climate changes. At the other side, buildings are recognized as big energy consumers which produce over a third of global greenhouse gas emissions. Building energy efficiency today is a prime objective for energy policy at regional, national, and international levels.*
Green building is a practical and intuitive approach to creating environmentally sound buildings, which combines age-old tradition and design processes, modern building science, and technology and materials application. Green buildings incorporate sustainable features in their design and construction. The main goals of green building development are to design buildings that use less energy, cost less for operation and maintenance, limit the impact on the environment, and create places for people to work and live that promote health and productivity. This paper represents the main green buildings standards for green building rating and classification of the categories for the achievement of the green building design, which are recognized by the green building community.

Keywords: *buildings; green building technology; green building standards; green building categories.*

1. INTRODUCTION

In the recent years, energy security and energy stability become the cardinal questions of the entire world economy, economic and social system. The rapid population growth causes a steady increase of energy needs, so the humanity is in the constant researching of the energy sources that would cover the growing energy needs. Energy needs in a modern world today are covered with conventional energy sources, mainly fossil fuels - non-renewable energy sources, which have a large number of negative impacts, especially on the environment.
In the most countries, buildings are the largest energy consumers and they have a significant CO_2 emissions. Approximately 160 million buildings of the EU are estimated to consume over 40% of total energy consumption and they are responsible for over 40% of CO2 emissions. The share of energy and greenhouse gas emissions associated with buildings is even larger in the US, amounting to 48% of total emissions [1].
In developed countries, emissions from buildings, and their portion in the total GHG emissions, have been increasing over the last fifty years. In developing countries, at the other side, the share of buildings on total energy consumption and total CO_2 emissions is much lower. However, with rapid industrialization and urbanization in these countries, energy use and the GHG emissions associated with buildings are increasing rapidly. Projections for GHG emissions associated with buildings estimate that worldwide GHG emissions will reach about 15 billion CO_2 by 2030, with Asian countries contributing to about 30 % of such emissions [1]. In Serbia, the building sector consumes more than 50% of the total energy consumption [2].
As the buildings consume a significant part of energy, it is necessary to investigate all aspects of energy consumption in order to minimize the total energy consumption. In EU countries, heating systems consumes around a third of the total building energy consumption, while in Serbia it is at the level of even 60 % [3]. The rest part of energy consumption is related to the ventilation, lighting and appliances. The building envelope is a critical component for the energy losses and heating energy consumption, so it is very important to design energy efficient buildings or implement the principles for improving energy efficiency of already existing buildings.
Reducing the energy and GHG footprint in both existing and new buildings represents therefore a key challenge and opportunity to tackle global warming.

2. GREEN BUILDINGS TECHNOLOGIES

Green development is becoming more business-savvy. The two most obvious benefits of green development are long-term financial savings and returns on investments (ROI). Benefits and rewards for constructing green buildings vary by type of ownership, type of use, owner's and project team's level of investment, and the team's drive to build a sustainable building.
Green buildings incorporate sustainable features in their design and construction. The four main goals of green development are to create buildings that use less energy, cost less to operate and maintain, limit the impact on precious natural resources and create places for people to work and live that promote health and productivity. Buildings can be considered green if they incorporate sustainable elements that satisfy the four main goals of green, or sustainable, real estate development. Project owners can design and construct healthy, efficient buildings, without having to compromise functionality. These built environments are designed to conserve water and energy; use space, materials, and resources efficiently; minimize construction waste; create a healthful indoor environment, and incorporate improvements and technologies that provide real cost savings [4].
Conducting a building life cycle cost analysis in the design stage of a project can help show the financial benefits of a green building versus a conventional structure. It is especially useful when project alternatives that fulfil the same performance requirements but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings [5]. Figure 1 represents the benefits from green buildings, in accordance to the investigation of several authors.

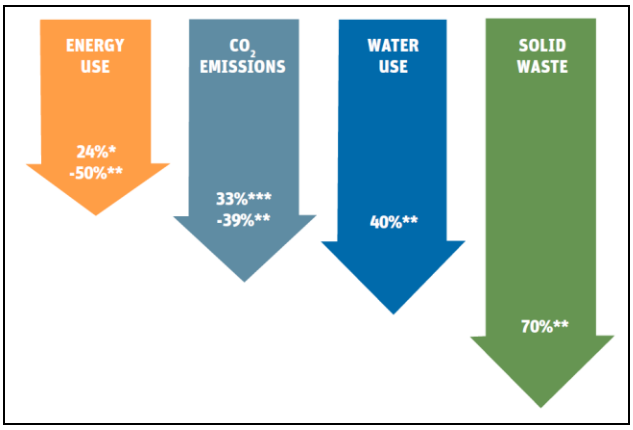

Fig.1. Green buildings benefits

Energy targets in new buildings are becoming more stringent and an increasing number of buildings are aiming to be carbon neutral. This means that the building generates sufficient energy from on-site renewable energy systems, such as photovoltaic systems, to meet its own needs. These buildings are very energy efficient and have large renewable energy and battery storage systems that are capable of generating and storing sufficient energy to enable the building to run continuously without mains power.
Incorporating more energy efficient greener technologies in buildings has a wide range of benefits, including:

- Reducing carbon emissions and therefore global warming impacts
- Reducing impact of mains power outages
- Reducing negative health impacts associated with pollution from coal-fired power stations
- Reducing operational costs
- Improving internal environments as a result of better daylighting, natural ventilation and local control.

As a result, there is an increasing choice of green technologies and techniques that can be applied in buildings to reduce energy consumption and environmental impacts.
Integrating green building technologies can be supported through a structured approach to the development of new buildings and the upgrading and refurbishment of existing buildings.
A very important consideration is ensuring that environmental impact and energy is considered, and addressed, at the onset of the project. The potential for addressing environmental impacts and energy efficiency and therefore achieving energy savings is very high at the beginning of the project. This, however, drops rapidly later, which means that significant additional effort, and often costs, are required if this is only addressed at a later stage in the development of projects.
If early strategic decisions are wrong, the potential energy savings will be reduced and significantly more effort will be required to achieve energy savings.

3. GREEN BUILDINGS STANDARDS

One of the unique qualities of green buildings is that no matter the budget, it is possible to incorporate some aspect of sustainability into every project. Different rating systems exist that evaluate the level of sustainability of a project. The more sustainable features included in a project, the higher the level of certification that could be awarded. Today, there are numerous rating systems worldwide that certify green buildings.
Several standards, methodologies, and tools have been put in place to assist organizations in delivering excellent environmental performance concerning their building stock. The document discusses alternative offerings such as LEED, Green Globes, Green Building (Europe), BREEAM, the International Green Construction Code, the German Sustainable Building Council, the Green Star from Australia, Estidama from the UAE, and CASBEE from Japan.
Figure 2 demonstrates the prevalence of these types of certifications – the yellow countries are in the process of developing certification programs [6]. This graphs shows that the demand for green buildings is growing and that certification programs are fast becoming the norm in the building construction industry.
In this paper, the standards that have the widest application will be discussed.

Fig.2. Green building certifications worldwide

3.1. LEED Standard

LEED (Leadership in Energy and Environmental Design) is a certification program, i.e. national standard developed by the United States Green Building Council (USGBC) to certify sustainable buildings. Since its inception in 1998, LEED has grown and become the widely used green building program across the globe, to encompass over 50000 projects in 50 US States and 135 countries worldwide.
The hallmark of LEED is that it is an open and transparent process where the technical criteria proposed by the LEED committees are publicly reviewed for approval by the more than 10,000 membership organizations that currently constitute the USGBC [7].
LEED is a third-party certification program and the nationally accepted benchmark for the design, construction and operation of high-performance green buildings. The USGBC operates 10 LEED Green Building Rating Programs for specific project types: for new construction (LEED-NC), for Existing Buildings (LEED-EB), for Commercial Interiors (LEED-CI), for Core & Shell (LEED-CS), for Schools, for Retail-New Construction, for Retail and Commercial Interiors, for Healthcare, for Homes, and for Neighborhood Development. LEED-NC (for New Construction) is the most widely used standard.

Fig.3. LEED credit categories

LEED standard promotes a whole building approach to sustainability by recognizing performance in five key areas of human and environmental health (Fig. 3):

- sustainable site development,
- water savings,
- energy efficiency,
- materials selection,
- indoor environmental quality.

Certification can be achieved in the four levels: Certified, Silver, Gold and Platinum. The level of LEED certification obtained is determined by the number of achieved credits (in points).

3.2. Green Globes

Green Globes is an online building assessment tool that evaluates and rates the environmental performance of new and existing buildings, and interior fit-ups. It is used by the federal government and the private sector.
The Green Globes assessment and rating system is the result of more than eleven years of research and refinement by a wide range of prominent international organizations and experts.
The genesis of the system was the Building Research Establishment's Environmental Assessment Method (BREEAM). In 1996, the Canadian Standards Association (CSA) published BREEAM Canada for Existing Buildings. In 2000, the system took a leap forward in its evolution, becoming an online assessment and rating tool under the name Green Globes for Existing Buildings. In 2004, Green Globes for Existing Buildings was adopted by BOMA (Building Owners and Managers Association of Canada), where it now operates under the name BOMA BESt [8].
Today, the Green Globes system is used by large developers and property management companies, including, the Canadian federal government, which has adopted the programme for its entire real estate portfolio.
The objectives of Green Globes are to:

- Evaluate energy and environmental performance of buildings.
- Encourage peer reviews of design and management practices.
- Increase awareness of environmental issues amongst building owners, designers and managers.
- Provide action plans for improvement at varying stages of project delivery.
- Provide certification and awards for green building design and management.

Green Globes assists in the design of buildings that are energy and resource efficient, achieve operational savings and which are healthier and more comfortable to work and live in.
Green Globes for New Construction (Green Globes NC) was designed to be a rating system designed specifically for new construction, major renovations, and additions.
Green Globes NC is a smart alternative for rating and certifying new construction designs owing to these four key attributes:

- A comprehensive environmental assessment protocol using accepted criteria

- Best practices guidance for designing sustainable new construction, major renovation, and additions
- A practical and cost-effective approach using licensed, independent third-party professionals as assessors to work with owners and design teams
- Based on the only national consensus green building standard for new commercial construction, developed in 2010 by the Green Building Initiative and acknowledged by the federal General Services Administration and the US Department of Defense.

3.3. Green Building (Europe)

The Green Building Programme (GBP) is a voluntary programme that started in 2005. It is meant to enhance the realization of cost-effective energy efficiency potentials by creating awareness and providing information support and public recognition to companies the top management of which is ready to show actual commitment to adopt energy efficient measures in non-residential buildings [1].
These are the important requirements for participation:

- an Energy Audit;
- an Action Plan;
- execution of the Action Plan;
- commitment to report energy consumption on a regular basis.

GBP provides documents defining the technical nature of an appropriate commitment for each energy service covered in the programme. GBP investments use proven technology, products and services for which efficiency has been demonstrated. Being a Green Building Partner gives a company the chance of presenting its actions for its organization's and the world's sustainable future to the broad public. The company will be an important multiplier to encourage other organizations to follow suit.
The benefits are:

- Recognition and approval of the action for enhancing the energy efficiency of the building stock by the European Commission
- Competitive advantages as an organization being certified for its responsibility in the field of energy efficiency
- Presentation and communication of the organization and the Good-Practice-Example within the public relations of the GB Program.

GBP are complementary to the Building Energy Performance Directive as it stimulates additional savings in the non-residential building sector.

3.4. BREEAM – Europe

BREEAM (Buildings Research Establishment (BRE) Environmental Assessment Method) is a voluntary environmental assessment method for buildings established in the UK by BRE. BREEAM is one of the world's foremost environmental assessment methods and rating systems for buildings [4]. There are over 200 000 buildings with certified BREEAM assessment ratings and over a million registered for assessment since it was first launched in 1990.
BREEAM sets standards for best practice in sustainable building design, construction and operation and has become one of the most comprehensive and widely recognized measures of a building's environmental performance.
A BREEAM assessment uses recognized measures of performance, which are set against established benchmarks, to evaluate a building's specification, design, construction and use. The measures used represent a broad range of categories and criteria from energy to ecology. BREEAM addresses wide-ranging environ–mental and sustainability issues and enables developers, designers and building managers to demonstrate the environmental credentials of their buildings to clients, planners and other initial parties. The standard looks at environmental impacts in the areas:

- Management
- Health and Wellbeing
- Energy, Transport
- Water
- Material and Waste
- Land use and Ecology
- Pollution.

It can be used to assess the environmental performance of any type of building (new and existing). Credits are awarded in each of the above areas according to performance (Fig. 4). A set of environmental weightings then enables the credits to be added together to produce a single overall score. Certifications can be achieved in the levels: Pass, good, very good, excellent and outstanding.

Fig.4. BREEAM credit categories and points [9]

3.5. International Green Construction Code

In 2009, the International Code Council launched the development of a new International Green Construction Code (IgCC) initiative, subtitled "Safe and Sustainable: By the Book," committed to developing a model code focused on new and existing commercial buildings addressing green building design and performance.
The IgCC applies to all occupancy-types except low-rise residential buildings under the International Residential Code [10]. The IgCC is not applicable to equipment or systems used primarily for industrial or manufacturing purposes. The new code is intended to provide "minimum requirements to safeguard the environment, public health, safety and general welfare" and reduce the negative impacts and increase positive impacts of the built environment on the natural environment and building

occupants. As such, it covers natural resources, material water and energy conservation, operations and maintenance for new and existing buildings, building sites, building materials, and building components (including equipment and systems).

3.6. German Sustainable Building Council

The German Sustainable Building Council (DGNB) focuses heavily on the establishment and further development of its certification system. As a tool for the assessment and certification of sustainable buildings, it is one of the leading systems worldwide, mainly due to its comprehensive quality concept, which takes equal account of economics, ecology, and socio-cultural aspects and is based on a holistic view of the building's entire life cycle. It is therefore possible to define sustainability targets beginning in the planning phase [11].
The results are anticipated to be future-oriented buildings with high quality standards documented by the DGNB certificate in gold, silver, or bronze. The DGNB System can also be used outside of Germany. Due to its conformity with present and future EU regulations, it is a tool that can ensure high building quality and performance.
The criteria in the DGNB's core system define sustainable building in six fields:

- Ecological quality,
- Economic quality,
- Sociocultural and functional quality,
- Technical quality,
- Process quality,
- Site quality.

The site quality does not play a role in the assessment of the total performance index.

Fig.5. DGNB criteria [12]

3.7. Green Star (Australia)

Green Star is a voluntary environmental rating system for buildings in Australia. It was launched in 2003 by the Green Building Council of Australia - an organization that is committed to developing a sustainable property industry for Australia by encouraging the adoption of green building practices [13]. The system considers a broad range of practices for reducing the environmental impact of buildings and to showcase innovation in sustainable building practices, while also considering occupant health and productivity and cost savings.

Green Star is a comprehensive, national, voluntary environmental rating system that evaluates the environmental design and construction of buildings. With more than 4 million square metres of Green Star certified space around Australia, and a further 8 million square metres of Green Star-registered space, Green Star has transformed Australia's property and construction market.
Green Star was developed for the property industry in order to:

- Establish a common language;
- Set a standard of measurement for green buildings;
- Promote integrated, whole-building design;
- Recognize environmental leadership;
- Identify building life cycle impacts, and
- Raise awareness of green building benefits.

Green Star covers a number of categories that assess the environmental impact that is a direct consequence of a project site selection, design, construction and maintenance. The 9 categories included within all Green Star rating tools are:

- Management;
- Indoor environment quality;
- Energy;
- Transport;
- Water;
- Materials;
- Land use and ecology;
- Emissions;
- Innovation

Certifications can be achieved in the levels of 1-6 stars, where 6 is the highest level (Fig. 6).

Fig.6. Green Star rating [14]

3.8. Estidama (UAE)

Estidama, which means 'sustainability' in Arabic, is the initiative that will transform Abu Dhabi into a model of sustainable urbanization. Its aim is to create more sustainable communities, cities and global enterprises and to balance the four pillars of Estidama: environmental, economic, cultural and social (Fig. 7).
Estidama began in 2009 and is the first programme of its kind that is tailored to the Middle East region. In the immediate term, Estidama is focused on the rapidly changing built environment [15]. It is in this area that the UPC is making significant strides to influence projects under design, development or construction within the Emirate of Abu Dhabi.

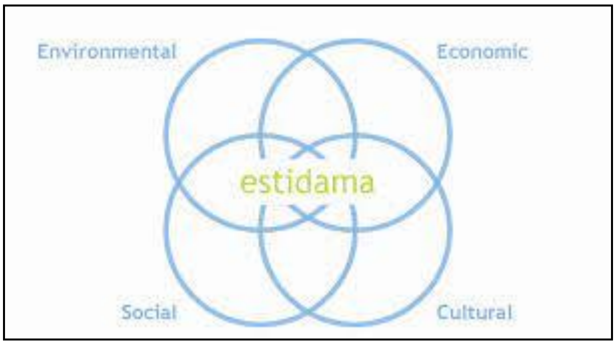

Fig.7. Four Pillars of Estidama

Estidama will continually evolve to embrace the rapidly changing concepts for sustainability, and ground them in the environmental, social, cultural, and economic needs of the Gulf Cooperation Council (GCC) region.
The Pearl Rating System for Estidama aims to address the sustainability of a given development throughout its life cycle from design through construction to operation. The Pearl Rating System provides design guidance and detailed requirements for rating a project's potential performance in relation to the four pillars of Estidama.
The Pearl Rating System is organized into seven categories that are fundamental to more sustainable development. These form the heart of the Pearl Rating System:

- Integrated development process: Encouraging cross-disciplinary teamwork to deliver environmental and quality management throughout the life of the project.
- Natural systems: Conserving, preserving and restoring the region's critical natural environments and habitats.
- Livable buildings: Improving the quality and connectivity of outdoor and indoor spaces.
- Precious water: Reducing water demand and encouraging efficient distribution and alternative water sources.
- Resourceful energy: Targeting energy conservation through passive design measures, reduced demand, energy efficiency and renewable sources.
- Stewarding materials: Ensuring consideration of the 'whole-of-life' cycle when selecting and specifying materials.
- Innovating practice: Encouraging innovation in building design and construction to facilitate market and industry transformation.

3.9. CASBEE (Japan)

Comprehensive Assessment System for Building Environment Efficiency (CASBEE) is a method for evaluating and rating the environmental performance of buildings and the built environment. CASBEE has been designed to both enhance the quality of people's lives and to reduce the life-cycle resource use and environmental loads associated with the built environment, from a single home to a whole city.

CASBEE was developed in Japan, at the beginning of 2001. The family of assessment tools is based on the building's life cycle: pre-design, new construction, existing buildings, and renovation. CASBEE presents a new concept for assessment that distinguishes environmental load from quality of building performance.
CASBEE was developed according to the following policies [16]:

1) The system should be structured to award high assessments to superior buildings, thereby enhancing incentives to designers and others.

2) The assessment system should be as simple as possible.

3) The system should be applicable to buildings in a wide range of applications.

4) The system should take into consideration issues and problems peculiar to Japan and Asia.

CASBEE major categories of criteria include the following:

1) Building Environmental Quality and Performance
   - Indoor environment (noise and acoustics, thermal comfort, lighting and illumination, and air quality),
   - Quality of services (functionality and usability, amenities, durability and reliability, flexibility and adaptability),
   - Outdoor environment on site (preservation and creation of biotope, townscape and landscape, and outdoor amenities).

2) Building Environmental Loadings
   - Energy (thermal load, use of natural energy, efficiency of systems, and efficient operations),
   - Resources and materials (water conservation, recycled materials, sustainably harvested timber, materials with low health risks, reuse and reusability, and avoidance of CFCs and halons),
   - Off-site environment (air pollution, noise and vibration, odor, sunlight obstruction, light pollution, heat island effect, and local on local infrastructure).

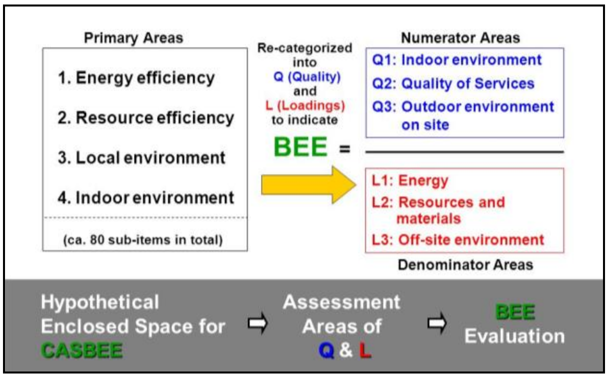

Fig.8. Assessment Area of CASBEE rating system

4. GREEN BUILDING CATEGORIES

In order to further define green buildings, categories for achievement are recognized by the green building community [4]. While they are not universal, they structure the different technologies and help to understand the broader concept. These categories are:

5. GREEN BUILDING CATEGORIES

In order to further define green buildings, categories for achievement are recognized by the green building community [4]. While they are not universal, they structure the different technologies and help to understand the broader concept. These categories are:

1) Site Selection

This area includes next elements: type of infrastructure available, the proximity to public transportation, storm water management options and roofing.

2) Water Efficiency

Water efficiency limit the use of water inside and outside the building by considering water demand reduction like low-flow restroom fixtures and high-efficiency irrigation systems and supply like use of storm water or grey-water (water used from showers, wash basins, and laundry) recycling.

3) Energy Efficiency

Energy Efficiency focuses on ways to reduce demand by incorporating energy efficiency features such as passive design like natural shading and lighting, high efficiency lighting, building controls, effective HVAC management and also includes supplying renewable energy by using technologies like solar photovoltaic panels, solar hot water heaters among others.

4) Materials and Resources

Material and resources include reduction of waste in construction and operation, the way the construction materials are disposed of and what materials are included in the building finishes with the objective to reduce waste to be disposed at landfills.

5) Indoor Environmental Quality

Indoor Environmental quality is focused on keeping the building healthy for the building occupants, by regulating thermal comfort, increasing natural lighting, improving indoor air quality, and minimizing noise levels, therefore reducing absenteeism and increasing occupant productivity.

These five categories can help designers and builders select which sustainable features to include in a building project. Often these categories are interrelated, e.g. improved natural lighting provides better indoor environmental quality and at the same time reduces electricity demand and cost for artificial lighting. If the goal is to save money on energy, then the best place to focus the project is on energy efficiency measures. When the cost-benefit analysis is completed, the owners and builders can determine which features to include in the final project.

6. CONCLUSION

Green building technologies describe technologies and techniques which are used in built environments for minimizing the environmental impacts while ensuring that buildings are able to accommodate the functions they have been designed for and are comfortable and productive to live and work in.

Green building technologies not only have to have a mitigation function (to reduce carbon emissions), they also have an adaptation function (to help building accommodate project climate changes) as the earth is already experiencing global warming.

Green building standards are available for almost every type of building and these standards are well developed and continuously being updated. These standards cover all phases of a building's life cycle from design through demolition. They are also available in a number of national standards and codes.

Buildings that have been designed with sustainability standards in mind need to be operated and maintained using sustainability standards. Buildings that were not designed to meet sustainability standards when they were built can also be upgraded to meet sustainability standards that have been put in place for existing buildings.

Green building technologies and appropriate building standards are essential for reducing energy consumption globally, as well as for reducing greenhouse gas emissions.

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REFERENCES

[1] Smiciklas J. at all, GO GREEN - Sustainable buildings, Septembar 2021, www.itu.int/ITUT/climatechange/ess/index.html

[1] Bojić M., Nikolić N., Nikolić D., Skerlić J., Miletić I., A simulation appraisal of performance of different hvac systems in an office building, *Energy and Buildings*, 43/6, p. p. 2407-241, 2011

[2] Nikolic D., Skerlic J., Radulovic J., (2017). Energy efficient buildings – legislation and design, *Proceeding of the 2nd International Conference on Quality of Life*, 2017, p. 55-60, Kragujevac, Serbia

[3] Breisinger M., Diez M. and Tagwerker C., Green building workbook, IDB, 2012.

[4] Gibberd J., Green building technologies, CSIR, 2020

[5] http://www.pikeresearch.com/wordpress/wp-content/uploads/2010/05/GBCP-10-Executive-Summary.pdf, accessed 2022-05-09

[6] https://www.cedengineering.com/userfiles/Leed%20Rating%20System.pdf, LEED rating system, accessed 2022-05-09

[7] Green globes – Design for new buildings and retrofits, ECD Energy & Environment Canada Ltd., Canada, 2004.
[8] https://www.termoservice-greenbuild.com/services/green-building/breeam-certification-facilities, Green Star, accessed 2022-05-11
[9] The American Institute of Architects, Guide to IgCC, 2011
[10] Mishra A., Kauskale L., The analysis of the green building supporting organisations in the Scandinavian countries and Baltic states, *Baltic Journal of Real Estate Economics and Construction Management*, Vol. 6, pp. 201-219, 2018
[11] https://blog.dgnb.de/en/sustainable-building/, Sustainable Buildings, accessed 2022-05-11
[12] https://www.gbca.org.au/uploads/91/2139/Introducing_Green_Star.pdf, Green Star, accessed 2022-05-12
[13] https://www.nzgbc.org.nz/greenstar, BREEAM certification, accessed 2022-05-12
[14] Pearl Community Rating System: Design & Construction, The Pearl Rating System for Estidama,, Version 1.0, Abu Dhabi Urban Planning Council, 2010
[15] Fowler K.M., Rauch E.M., Sustainable Building Rating Systems, Pacific Northwest National Laboratory, USA, 2006
[16] CASBEE for Property Appraisal, Japan Sustainable Building Consortium (JSBC), Tokyo, Japan, 2009

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SAVING ENERGY THROUGH THE USE OF RENEWABLE ENERGY SOURCES TO LOW CARBON CITIES

Ana RADOJEVIĆ
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Blaža STOJANOVIĆ

Abstract: *In the field of energy, Europe is facing challenges such as high import dependence, low diversification, high and volatile energy prices, growing global energy demand, security risks affecting producer and transit countries, growing threats from climate change, insufficient energy efficiency, as well as an increasing share of renewable energy sources (RES). Climate change has been identified as one of the biggest challenges, and European energy policy is increasingly focused on tackling this threat, advocating for reducing greenhouse gas (GHG) emissions, especially CO_2 emissions. The European Parliament wants the new energy policy to support the goal of reducing GHG emissions in the EU by 55% until 2030 and achieving a zero net emission rate by 2050. In the total world energy consumption, cities participate with over two thirds, and more than 75% of all GHG emissions come from cities. In the cities themselves, buildings are one of the biggest sources of CO_2 emissions. The EU directive on energy efficiency of buildings sets the goal that by 2050 the housing stock fund has zero CO_2 emissions. Thus, the goal is low-carbon cities, and the path to the goal may be the use of RES in cities. The paper uses examples from the world and Serbia to analyze how the use of RES leads to low-carbon cities.*

Keywords: *climate change; GHG emissions; RES; low-carbon cities; smart measurements*

1. INTRODUCTION

At the time of the energy crisis, we are witnessing the role of energy independence, ie the importance of a large share of the use of renewable energy sources and energy savings.
Today, more than half of the world's population lives in urban areas [1], and the number is constantly increasing. By the middle of the century, three-quarters of the global population is likely to live in urban areas, that is, in cities. Cities consume two-thirds of energy, generating more than 75% of global greenhouse gas emissions, which are a major cause of warming and climate change.
It undoubtedly follows from the above that cities are key actors and must be leaders in actively encouraging and enabling change, ie in facilitating the maximum use of renewable sources. The current trend of rising prices of electricity and other energy sources (gas, oil products, solid fuels) will become even more drastic with the worsening climate crisis. In order to ensure timely availability of energy and a better quality of life in local communities, in the future it is necessary for cities, ie. local self-governments, to take decisive steps towards the maximum use of renewable energy sources as soon as possible.
The cessation of the use of fossil fuels and the maximum use of locally available renewable energy sources is a crucial step in the fight against climate change.
The use of decentralized renewable energy sources is the primary tool for reducing the use of fossil fuels, mitigating the effects of the climate crisis and preserving nature and the environment. In addition, local renewable energy sources stimulate economic development, provide us with more choices in terms of our own energy production, and encourage local competition and innovation.

2. PLANNING for LOW-CARBON CITIES

Through the correct determination of strategic goals and planning the development of the city, the city administration defines the direction and speed of change and manages them in a coordinated manner, which enables real and systemic changes. This is an important advantage of cities.
Cities must know and plan what they need to ensure the low-carbon development of the city and enable everything

that citizens need for a quality life, not only now, but in 10, 20, 30 and more years.

The solutions we need must not trap us in new carbon emissions and further dependence on energy and energy imports, they must include investments in local sustainable energy.

Low-carbon cities have always been the subject of research by researchers around the world. All cities, especially those in low- and middle-income countries, are looking for solutions to control climate change. In order to achieve a city with low carbon emissions, participation and cooperation between governmental and non-governmental organizations and sectors has become more pronounced, so that all of them strive to achieve an integrated goal (low-carbon city).

One example of low-carbon city planning is Bangkok, where there is a planned decline in energy consumption and reduction of carbon emissions from 2000 to 2025. The year 2000 is used as the base year. The sustainability of the sixteen proposed policies and scenarios was analyzed using a multi-criteria decision-making approach. The results of this study provide insight into Bangkok's energy and carbon future and highlight the steps needed to promote a sustainable, low-carbon society. The most significant energy savings are in the transport sector, where the modal shift from private passenger vehicles to public transport systems has the potential to significantly reduce energy demand, carbon emissions and local air pollutants.

The Chinese government has been continuously developing several series of low-carbon city pilots since 2010. Research [2] shows how possible the goal of reducing carbon emissions can be achieved by building low-carbon pilot cities in different parts of China. The research showed that the effects of pilot policies vary significantly in different regions, depending on administrative power, GDP, carbon trade policy, use of new energy vehicles, energy structure, industrial structure and level of innovation.

Paper [3] shows that zero carbon buildings in Hong Kong can contribute to the creation of low carbon cities. In order to achieve the goals, it is necessary to raise public awareness of sustainable living, reduce energy use in other buildings and promote strategic urban planning. However, the most significant risks were identified as geographical barriers to domestic renewable energy production, high reliance on fossil fuels, and policy resistance by practitioners.

Empirical results in [4] have shown that pilot cities in China reduce carbon emissions by approximately 2.72% per year. In addition, the related loss of gross domestic product from 2013 to 2017 was approximately 1.19 trillion yuan. The analysis of the mechanisms clarified that the pilot cities reduced emissions by adjusting their industrial structure, promoting technological innovations of companies in order to increase their overall factor productivity and stimulating research and development of low-carbon technologies. The results of this study provide examples, supported by data, for the government to further promote its policy of building low-carbon cities.

In [5], the following solutions for achieving a low-carbon city in Tehran were identified with the help of Scenario Wizard software: Implementing urban green spaces such as local community gardens to enhance local participation and green employment, availability and density of pedestrian areas in order to develop non-motorized transport and reduce pollutants, conversion of the public buildings of the city into green buildings in order to move towards low carbon Tehran, creating the space for participation with the help of citizens to informing them, creating the national network for information sharing of urban projects and plans, financial supports for micro and creative industries in order to economic prosperity and increasing domestic production, implementing environmental plans to improve the ecological balance of the city, creating rooftop gardening on the roofs of public buildings, creating cool white ceilings (sealant coating with light colour) and installation of solar panels on the roofs of public buildings. Research has shown that Tehran's best scenario for moving to a low-carbon city would be the first scenario.

Paper [6] has shown that population size, household size and built - up land concentration are most responsible for carbon emissions. In this study, an integrated assessment method was used to assess the spatial carbon emissions, carbon sequestration capacity, emission-sequestration balance, and carbon resilience capacity of a Himalayan city using the ecological support coefficient.

The study [7] aims to analyze the CO_2 emission characteristics and spatial distribution in megacities among different countries, which is important for climate change mitigation. In this study, 12 megacities from China, Japan, and South Korea were selected as typical case studies for analysis. Results show that Chinese cities' CO_2 emissions are among the top four cities studies and are much higher when compared to the other sample cities in Japan and South Korea. Chongqing, Incheon, Tianjin, and Shanghai were the top four cities with the highest carbon intensity. The spatial distribution of urban carbon emissions varies widely. In Seoul, Tokyo Metropolis, and Beijing, 90% of carbon emissions are concentrated on 74.17%, 55.95% and 8.93% of the land area, respectively. The results of the driving forces and emission reduction targets analysis indicate that the three countries face different challenges and there are different action plans in each city accordingly. This study proposed the carbon emissions reduction targets and countermeasures in different industrial sectors, including an increased rate of the standardization of city CO_2 emission accounting systems and the decarbonization of the power industry, among others. These countermeasures will not only contribute to the analysis of CO_2 emissions but will also promote to the low-carbon city development and encourage the realization of urban sustainable development goals.

The paper [8] examines the roles of local governments that are in the early stages of a transformation from centralized to decentralized energy, while drawing on the lessons learned from the experience of three municipalities in Japan. This study found that the effective transitions to renewable energy in Japanese towns result largely from conflict-free policy coordination, which the author argues was produced by forward-looking local mayors.

This paper explores challenges that power sector faces in order to meet the decarbonization targets, and identifies certain modifications that should be made during the transition process. [9] Urban electrification with renewables is a crucial strategy for achieving low-carbon and climate-resilient communities. Given the different types of power customers (e.g., residential, commercial and industrial), this work develops a systematic and straightforward framework for the optimal planning of urban solar/wind/biomass (/natural gas) systems at neighbourhood scale using the actual real-time hourly electric loads. This study can help decision-makers in developing more effective policies and mechanisms to support the urban hybrid renewable energy systems.

3. EXAMPLES OF THE USE OF RES IN CITIES IN THE PROCESS OF DECARBONIZATION

There are different ways to achieve the goal of low-carbon cities, and most of them involve the use of renewable energy sources. The process of producing electricity, district heating systems, urban transport, the concept of a smart city, as well as the use of biomass, can be some of the ways to achieve climate-neutral cities.

When taking into account the general terms on which the global green and low-carbon transition takes place, it can be affirmed that the use of clean and renewable energy, including wind, hydro, solar, etc., is an alternative to the traditional energy sources. The renewable energy industry possesses considerable potential, and has recently become the center of the global energy landscape. Therefore, this article refers to the rolling-window Granger causality test, in order to explore the role of renewable energy (RE) in reducing the GHG emissions. By studying the interactions that take place between RE consumption and carbon dioxide (CO_2) emissions, we find that the negative impact of RE on CO_2 indicates that the replacement role of RE has become increasingly prominent, for it to effectively contribute towards the realization of carbon emission reduction. The results in this regard are consistent with the energy-environment model, suggesting that RE has an excellent performance in achieving carbon neutrality. In fact, CO_2 usually exhibits a negative effect on RE, which indicates towards the predictability of environmental quality to the development potential of renewable energy. [10]

The increasing level of carbon emissions is one of the most serious concerns in human history facing in today's world. Different countries adopt different policies and approaches to mitigate climate change severity. The current study evaluates the effect of carbon emissions, renewable energy sources, ICT, governance, and GDP in Morocco employing a time-series dataset over the period of 1985–2020. In this paper, we utilized the dynamic ARDL simulations model to explore the association among carbon emissions, renewable energy sources, ICT, governance, and GDP. The ARDL bounds test reveals a long-run connection among the variables. The findings suggest that renewable energy sources (i.e. solar, wind, hydroelectric), ICT, and effective governance are the key indicators to reduce carbon emissions. In addition, we utilized the Granger causality test to probe a causal connection between the study variables. The outcomes have long-run implications for carbon emissions degradation and Morocco's policy towards the fight against climate change. [11]

A transition towards long-term sustainability in global energy systems based on renewable energy resources can mitigate several growing threats to human society simultaneously: GHG emissions, human-induced climate deviations, and the exceeding of critical planetary boundaries. However, the optimal structure of future systems and potential transition pathways are still open questions. This research describes a global, 100% renewable electricity system, which can be achieved by 2050, and the steps required to enable a realistic transition that prevents societal disruption. Modelling results show that a carbon neutral electricity system can be built in all regions of the world in an economically feasible manner. This radical transformation will require steady but evolutionary changes for the next 35 years, and will lead to sustainable and affordable power supply globally. [12]

When we talk about the process of decarbonization in Serbia, several authors first dealt with the decarbonization of electricity production, at the level of the whole country. The results of the [13] reveal that hydropower and biomass have the highest potential among available renewable energy sources in decarbonization of electricity production. The paper [14] shows that, in the longer term, technologies that would most influence the market model will be distributed energy sources, demand response and energy storage, but it is also obvious how very important adequate policy measures are for the configuration of the decarbonized future. Interactions among technologies, system rules and market codes will trace the path of market model development. Serbia plans to shut down eight coal-fired power units with a capacity of 622 MW and a production of 1717 GWh per annum by 2024, but also to build a new 350 MW with a planned production of 2200 GWh.

3.1. Production of electricity from renewable energy sources

The paper [15] analyzes the use of renewable energy (RE) for electricity in 45 Indian cities within the Smart Cities Mission and its results. The analysis shows that the penetration of RE in cities is low. In addition to producing electricity in cities, those with the best performance could successfully use renewable energy outside city limits through regulatory incentives. The potential and strategies for exploiting more RES in cities were presented. The challenges of greater adoption of renewable energy sources in cities and necessary policy recommendations are also discussed.

3.2. Use of natural gas in district heating systems

Air pollution, caused by the use of fossil fuel, has been an environmental plague in China. It has a strong negative impact on human health. Since the costs of damage to health are not born by the pollution producers, these costs translate to social externality. Policies have an important role in optimizing resource allocation, such as penalizing the pollutant producers and incentivizing clean energy development. Among others, replacing coal with natural gas for heating represents an important example of air quality improvement measures. This paper presents a study that evaluates the health impacts from air pollution and the external cost of the “Coal-To-Gas” policy in district heating using Changping District (Beijing, China) as an example. Four scenarios were considered based on the historical and standard PM2.5 concentration. Results show that PM2.5 is responsible for causing an increase of 40% premature deaths in 2015 and that the monetary value of damage to health is higher than 1.2 billion CNY. In 2016 and 2017, the reported air quality was better than that in 2015. As a result, 13.3% and 26% premature deaths caused by air pollution were avoided in 2016 and 2017 compared to 2015 respectively. If the PM2.5 concentration level were to be reduced to national standard, the number of premature deaths attributed to PM2.5 could further decrease to 47.7% compared to 2015. Overall, the Coal-To-Gas policy in district heating reduces 0.017%~0.45% of premature death caused by air pollution each year. Air pollution reduction policies, which are expected to improve air quality together in the future, and the specific policy of Coal-To-Gas in district heating, could make great contribution to reducing the premature death caused by environmental problem and need more attention from the government and the public. [16]

3.3. Smart cities

Among the main components of a smart city, the energy system plays a key role, while the use of renewable energy sources has proven to be a significant contribution to reducing pollutant emissions and improving the quality of the environment. The use of renewable energy technologies very much, as part of the smart city concept, could make a significant contribution to a society with a low-carbon economy. The paper [17] fully presents the main components and roles of renewable energy sources (such as solar energy, wind, geothermal energy, hydropower, ocean and biofuels) used for smart city. In addition, the integration of forms of renewable sources into the energy systems of smart cities has been analyzed in detail on the basis of technical and economic criteria. Finally, existing challenges and future scenarios were discussed in detail to clarify the progress and perspective of smart renewable energy systems for a smart city. In general, the integration of renewable energy sources into the energy systems of a smart city is an insightful perspective and a solution aimed at achieving a cleaner process and more sustainable development.

3.4. Public transport

It is essential to understand the types and characteristics of urban transport CO_2 emissions and propose differentiated CO_2 emission reduction measures and formulate renewable energy use strategy, with a view to sequentially achieving the peak of urban transport CO_2 emissions. Based on the analysis of driving factors of urban transport CO_2 emission, this paper establishes a classified index system and then adopts the Gaussian mixture model (GMM) and expectation–maximization (EM) algorithm to cluster the trends of transport CO_2 emissions peak in 672 municipal cities in China. The results show that the model can effectively identify the differences between different cities and divide them into five types, namely the types of public transport demonstration, emission pressure, low carbon potential, population loss, and high carbon pressure, the proportion of urban transportation carbon emission in these five cities is 44.39%, 22.19%, 18.21%, 7.66% and 7.55%. Moreover, by analyzing different energy endowment characteristics and geographical features, optimization suggestions are put forward for the transportation energy consumption of different cities to realize the efficient utilization of renewable energy. [18]

3.5. Use of biomass

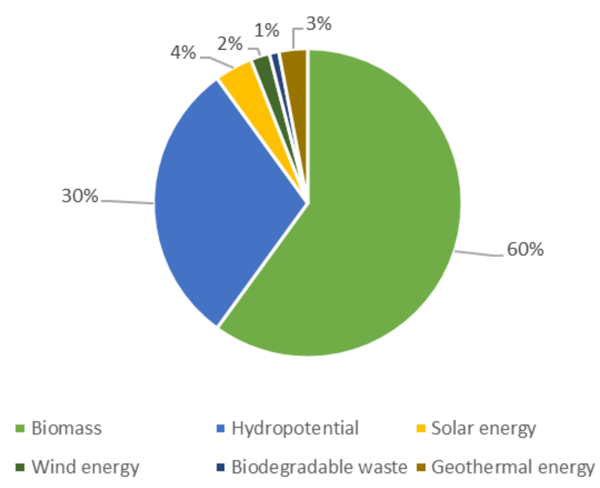

Fig.1. Potential of available renewable energy sources in Republic of Serbia

The available range of renewable sources in the Republic of Serbia shows that biomass has the greatest potential - 60%, out of which 32% is currently used. [19] Research shows that replacing fossil fuels with biomass in public buildings can lead to a reduction in CO_2 emissions of up to 94%, according to an analysis in the Serbian cities of Priboj and Pirot, where wood chips and biomass have been used for heating of the public buildings for the past six years.

4. CONCLUSION

At the time of the energy crisis, we are witnessing the role of energy independence, ie the importance of of the use of renewable energy sources and energy savings.
Today, more than half of the world's population lives in urban areas, and the number is constantly increasing. By the middle of the century, three-quarters of the global population is likely to live in urban areas, that is, in cities. Cities consume two-thirds of energy, generating more than 75% of global greenhouse gas emissions, which are a major cause of warming and climate change.
There are different ways to achieve the goal of low-carbon cities, and most of them involve the use of renewable energy sources. The process of producing

electricity, district heating systems, urban transport, the concept of a smart city, as well as the use of biomass, can be some of the ways to achieve climate-neutral cities.

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REFERENCES

[1] https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

[2] Liu, X., Li, Y., Chen, X., Liu J.: Evaluation of low carbon city pilot policy effect on carbon abatement in China: An empirical evidence based on time-varying DID model, *Cities*, Vol.No. 123, Article 103582, 2022

[3] Pan, W., Pan, M.: Opportunities and risks of implementing zero-carbon building policy for cities: Hong Kong case, *Applied Energy*, Volume 256, Article 113835, 2019

[4] Huo, W., Qi, J., Tong Yang, T., lu Liu, J., Liu M., Zhou, Z:: Effects of China's pilot low-carbon city policy on carbon emission reduction: A quasi-natural experiment based on satellite data, *Technological Forecasting and Social Change*, Volume 175, Article121422, 2022

[5] Boostani, P., Sadeghiha, M: Identification of critical uncertainties in Tehran in order to achieve the development of low carbon city by using scenario writing method, *Cleaner Engineering and Technology*, Volume 6, Article100405, 2022

[6] Ghosh, S., Dinda, S., Das Chatterjee, N., Dutta, S., Bera, D: Spatial-explicit carbon emission-sequestration balance estimation and evaluation of emission susceptible zones in an Eastern Himalayan city using Pressure-Sensitivity-Resilience framework: An approach towards achieving low carbon cities, *Journal of Cleaner Production*, Volume 336, Article 130417, 2022

[7] Sun, L., Liu, W., Li. Z., Cai, B., Fujii, M., Luo, X., Chen, W., Geng Y., Fujita, T., Le Y: Spatial and structural characteristics of CO_2 emissions in East Asian megacities and its indication for low-carbon city development, *Applied Energy*, Volume 284, Article 116400, 2021

[8] Takao, Y: Low-carbon leadership: Harnessing policy studies to analyse local mayors and renewable energy transitions in three Japanese cities, *Energy Research & Social Science*, Volume 69, Article 101708, 2020

[9] Bagheri, M., Hamid Delbari, S., Pakzadmanesh, M., A.Kennedy, C: City-integrated renewable energy design for low-carbon and climate-resilient communities, *Applied Energy*, Volume 239, pp. 1212-1225, 2019

[10] Yuan, X., Chi-Wei Su, Umar, M., Shao, X., Oana-Ramona LOBONŢ: The race to zero emissions: Can renewable energy be the path to carbon neutrality?, ***Journal of Environmental Management***, Volume 308, Article: 114648, 2022

[11] Khana, Y., Oubaiha, H., Zahra Elgourramib F:The effect of renewable energy sources on carbon dioxide emissions: Evaluating the role of governance, and ICT in Morocco, Renewable Energy, Volume 190, pp. 752-763, 2022

[12] Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., Solomon Oyewo, A., de Souza Noel Simas Barbosa, L., Breyer, C: Radical transformation pathway towards sustainable electricity via evolutionary steps, *Nature Communications*, Volume **10**, Article: 1077, 2019

[13] Pavlović, B., Ivezić, D., Živković, M: A multi-criteria approach for assessing the potential of renewable energy sources for electricity generation: Case Serbia, *Energy Reports*, Volume 7, pp. 8624-8632, 2021

[14] Ćorović, N., Gvozdenac- Urošević, B., Katić, N: Decarbonization: Challenges for the electricity market development — Serbian market case, *Energy Reports*, Volume 8, pp. 2200-2209, 2022

[15] Govindarajan, Krishnan, H., Ganesh, L.S.: Renewable energy for electricity use in India: Evidence from India's smart cities mission, ***Renewable Energy Focus***, Volume 38, pp. 36-43, 2021

[16] Xi, X., Li, H., Wallin, F., Avelin, A., Yang, X., Yu, Z.: Air pollution related externality of district heating – a case study of Changping, Beijing, *Energy Procedia*, Volume 158, pp. 4323-4330, 201

[17] Tuan Hoang, A., Viet Pham, V., Phuong Nguyen X: Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process, *Journal of Cleaner Production*, Volume 305, Article 127161, 2021

[18] Wang, M., Feng Li, T., Yuan, C., Tian, H., Tian, S: Research on vehicle renewable energy use in cities with different carbon emission characteristics, *Energy Reports*, Volume 8, Supplement 6, pp. 343-352, 2022

[19] http://indicator.sepa.gov.rs/pretrazivanje-indikatora/indikatorilat/allfindr/2edba915e97b466aab3bb6581e2db228

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MAINSTREAMING LOW CARBON URBAN DEVELOPMENT – DECARBONIZING CITIES

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Abstract: *For decades now, the climate changes have required great attention in sustainable development of the planet, and, same as reducing carbon emissions in the environment, they have become an absolute imperative for the future of the human civilization. Compliance with the Paris Agreement requires the transformation of national economies in order to meet net zero carbon emissions by the middle of the century. To achieve this, countries need to define long-term decarbonisation strategies with short- and medium-term actions to determine their ideal future scenario, while maximizing socio-economic benefits. Identifying new roads and fostering urban development with very low or neutral carbon content is a new challenge for government, industry and the community. Providing the capacity to generate and trade carbon credits in urban development could potentially help decarbonise cities. Carbon certification has also been identified as a way of recognizing and rewarding progressive urban development, which can show a true reduction in carbon. This paper describes the procedures that followed in order to support the creation of a decarbonisation trajectory for the transport and energy sectors. In this paper, we will discuss the technological path of deep decarbonization that supports reaching zero emissions by 2050. Certainly, innovations in decarbonisation will be the main source of wealth in the future. So far, it has been shown that technologies are available, the principles of urban design for decarbonisation are well understood, but management systems to facilitate and manage development at the municipal level are still largely lacking. If we succeed in developing such systems, processes, and mechanisms that target the built environment and reward positive behavior, we could begin to radically decarbonize our cities.*
Keywords: *Energy policy; smart measurements; decarburization of cities; greenhouse gas emissions;*

1. INTRODUCTION

The United Nations Framework Convention on Climate Change (UNFCCC) is an international agreement established in 1992. The convention's objective was to stabilize greenhouse gas (GHG) emissions across the world in order to respond to the global threat of climate change. The subsequent Kyoto Protocol established legally binding obligations for countries to reduce their emissions. Most recently, in 2016, the Paris Agreement was adopted to govern GHG emission reductions from 2020. These international treaties are designed to catalyze appropriate mitigation action across the world.

At the same time, European energy policy is increasingly becoming a significant tool in the fight against climate change, advocating for the reduction of GHG emissions. The European Parliament is in favor of stronger commitments to EU targets, and stresses that the new energy policy must support the goal of reducing GHG emissions by 55% in the EU by 2030 and achieving zero net emissions or climate neutrality by 2050. With the adoption of the latest amendment to the Directive on energy efficiency of buildings, in 2018, EU countries will have to establish stronger long-term renovation strategies, with the goal of the housing fund having zero CO2 emissions by 2050.

Two of the five main objectives of EU energy policy relate to decarbonisation: the decarbonisation of the economy and the transition to a low-carbon economy under the Paris Agreement, and encouraging the development of new and renewable forms of energy to better align and integrate climate change-related targets into the new market model.

The current policy agenda is based on the comprehensive integrated climate and energy policy adopted by the European Council on September 24, 2014 and revised in December 2018, which envisages achieving the following targets by 2030: reducing greenhouse gas emissions by at least 40 % compared to 1990. On November 30, 2016, the European Commission presented the Proposal for a Regulation on the governance of the Energy Union as part of the "Clean Energy for All Europeans" package [1].

According to the Regulation, each Member State should present an "integrated national energy and climate plan" by 31 December 2019, and every ten years thereafter. These long-term national strategies will set out a political vision for 2050, in order for member states to achieve the goals of the Paris Agreement. These integrated national energy and climate plans will include national objectives, contributions, policies and measures for each of the five dimensions of the energy union: decarbonisation, energy efficiency, energy security, the internal energy market, as well as research, innovation and competitiveness. The European Parliament also calls for stronger commitments to EU targets, and stresses that the new energy policy must support the goal of reducing EU greenhouse gas emissions by 55% by 2030 and achieving a zero net emission rate or climate neutrality by 2050.

2. WHY CITIES?

Today, close to 55% of the global population live in urbanized areas. By 2050 it is expected that this number will increase to over 65% [2]. In Europe, the level of demographic urbanization is approaching 74%. Because of all this, the European Commission's long-term strategy [3] recognizes cities as ideal places for transformative and sustainable solutions. Urban renewal and better spatial planning, including green spaces, can be the main ways to achieve the goal of net-zero GHG emissions by 2050 [4]. Cities consume over two-thirds of the total amount of energy consumed worldwide. Over 70% of all GHG emissions originate from cities [5].

The impact the urban environment has on contributing to the root cause of climate change cannot be understated.

Carbon dioxide (CO_2) is the most prevalent GHG emitted by human activity. CO_2 is the most commonly-used term when describing accounting for harmful GHGs. National and international carbon emissions accounting shows carbon as carbon dioxide equivalent (CO_2e). This includes the conversion of other GHGs, such as methane from landfill, into their equivalent CO_2 emissions based on their relative global warming potential. This form of accounting aligns with national and international measurement of CO_2 emissions) [6].

The application of low-carbon technologies for sustainable energy production and use requires the active involvement of local and regional communities. The reason for this is that cities around the world consume 78% of the world's energy and are responsible for more than 70% of global CO_2 emissions [7], due to energy production, transport, industry and the use of biomass [8]. Urban activities affect the environment both negatively and positively [9], leading to the need for cities to address climate change, reduce energy consumption and increase the use of renewable energy sources (RES) through the development of holistic plans based on environmental, social and economic aspects. To do so, city authorities need the support of appropriate methods throughout the value chain of urban development that address the growing demand for energy, changing demographic data, and creating infrastructure [10]. This is even more relevant given that a recent review of climate plans of 200 EU cities reveals that climate change planning in EU cities is largely determined by their local organizational capacity [11].

The EC strategy points the way forward to a carbon-neutral economy by referring to a set of joint actions:

- improving energy efficiency in buildings, which today are responsible for 40% of energy consumption;
- maximizing the deployment of renewables and the use of electricity to fully decarbonize Europe energy supply;
- embracing clean, safe and connected mobility, currently responsible for around a quarter of the GHG emissions in the EU;
- fostering circular economy as a key enabler to reduce GHG emissions, starting from reducing the input of materials through reuse and recycling, and significantly modernizing or replacing existing installations;
- developing an adequate and smart infrastructure ensuring optimal interconnection, especially to support the major developments framing the energy transmission and distribution landscape of tomorrow;
- reaping the full benefits of bio-economy enhancing capacity of agriculture and forestry to provide sufficient food, feed, and fibers as well as to support the energy sector and various industrial and construction sectors.
- enforcing carbon sinks, as important as reducing emissions, by maintaining and further increasing the natural sinks of forests, soils, and agricultural lands and coastal wetlands;
- tackling remaining CO_2 emissions with carbon capture and storage previously seen as a major decarbonisation option for the power sector and energy-intensive industries [12].

Several programs and voluntary initiatives such as the EU Covenant of Mayors Pact (CoM) [13] renamed as Covenant of Mayors for Climate & Energy, or the UN Global Compact of Mayors for Climate and Energy [14] or the C40 Cities Climate leadership group [15] strive to lead their partner cities towards sustainable development achievements, low carbon future design and improved quality of life of their citizens.

3. INTERNATIONAL CASE STUDIES

The UK government has committed to reduce its greenhouse gas (GHG) emissions by 80%, from 1990 levels, by 2050. Decarbonisation of transport and heat supply to buildings is recognized as a fundamental step in achieving this target. With cities being the largest producers of GHG emissions, they provide the biggest opportunity for climate change mitigation. Two contrasting visions of a 2050 target-compliant scenario are assessed against each other. One is based on higher usage of nuclear power and renewables, and the other is based on predominantly gas with carbon capture storage (CCS). An impact assessment is done on both scenarios to see how each scenario might perform over four evaluation criteria. The evaluation criteria provide insight into each scenario regarding: security of supply, costs, sustainability and feasibility of deployment. While both scenarios raise some issues on the feasibility of deploying certain technologies, the more favorable scenario, in terms of the study results, is the nuclear and renewables option. The renewable energy generating technologies included as part of the study – from largest to smallest in terms of capacity – are wind, solar photovoltaic, tidal and river hydro. [16] The results of the study provide an important contribution to academic debate on what might be the most effective approach to achieving the 2050 decarbonisation target.

Results for the city of Sao Paulo show that district cooling is cost-effective in the highest linear cooling density zones, with full penetration in zones with over 1100 kWh/m by 2050. This threshold diminishes with tighter carbon constraints. Heating is electrified in all scenarios, with electric boilers and air-source heat pumps being the main supply technologies for the domestic and commercial sectors respectively by 2050. In the most carbon constrained scenario with a medium decarbonized electricity grid, ground source heat pumps and hydrogen boilers appear as transition technologies between 2030 and 2045 for the commercial and domestic sectors respectively, reaching 95% and 40% of each sector's heat installed capacity in 2030. In the transport sector, ethanol cars replace gasoline, diesel, and compressed natural gas cars; compressed natural gas buses replace diesel and electric buses; and lorries continue using diesel. In carbon constrained scenarios, higher usage of electric cars and buses are envisioned, while no change is observed for lorries. Finally, the most expensive scenario was only 6% more expensive than the reference scenario, meaning that achieving decarbonisation targets is not much costlier when comparing scenarios from a system-wide perspective [17].

In Ireland, decarbonisation technologies' pathways were researched as to which of them may aid in meeting national decarbonisation targets, and their potential role at local administrative area scale was evaluated. Application of this method resulted in a small number of larger industrial and commercial buildings, representing only 4% of the sector's buildings, were found to account for 38% of its decarbonisation potential. Future carbon emission scenarios identified that electricity demand may be expected to increase for the industrial and commercial sector by 2030, and that the technological potential for current photovoltaic systems have the potential to reduce GHG emissions by 4% more than currently planned Irish grid-scale decarbonisation trajectories. The method may be adopted at European scale, using local data on climate and building attributes, and is applicable at national, regional and local scales. The paper concludes with a review of technologies which may aid further decarbonisation studies, which include improved data availability for 3D building generation, and enabling technologies such as machine learning algorithms applied to satellite imagery [18]. This paper describes a framework for estimating the effectiveness of photovoltaic and rainwater harvesting technology deployment on industrial and commercial zoned buildings to facilitate reducing national GHG emissions.

There is a number of examples around the world on how the parts of cities have been transformed into low-carbon places. BedZED - UK is one of them, as well as Vauban, in Freiburg - Germany and Hammarby Sjostad, in Stockholm - Sweden.

BedZED is small, dense, mixed-use eco-development located in the southern suburbs of London. It is built on a brownfield site and situated close to a rail station. From its inception, it pushed the boundaries, testing and showcasing several new low-carbon technologies and urban design elements. Completed in 2002, BedZED is one of the original and hence most well-known global examples of a grass roots sustainable development. The name BedZED originates from Beddington Zero (Fossil) Energy Development and was originally designed to be a carbon-neutral precinct [19].

The aim was to generate enough zero-carbon energy onsite to meet the electricity, heating and hot water needs of the development, while feeding excess energy into the grid.

Despite an overarching focus on operational energy, the designers of the development integrated a variety of sustainability measures and initiatives that targeted emissions from a wide range of areas, including water, waste, materials and transport. The development's broad focus on sustainability made it an outstanding example of what is possible at a small-scale and very local level. Some of the initial low carbon, sustainability features included the following:

- highly energy-efficient three-story townhouses that use solar passive design, including passive ventilation and daylighting to reduce the need for artificial heating, cooling and lighting;
- low-carbon materials sourced locally where possible;
- energy- and water-efficient appliances;
- grey water-recycling facilities onsite as well as rainwater tanks;
- solar photovoltaic panels on roofs;
- biomass-fuelled, combined heat and power (CHP) plant providing zero-carbon electricity and district heating to the development (later changing to a gas district-heating system);
- mixed use, combining office space and residential dwellings, to reduce transport emissions from commuting;
- transit-oriented (i.e. situated next to a train station to promote low-carbon transportation) to reduce personal transport emissions; and
- provision and encouragement of local food production (including rooftop gardens), reducing food miles and associated emissions.

In addition to the numerous low-carbon initiatives, many other broad sustainability features were included such as affordable housing and a range of other housing tenures [20], community facilities and open space, and the preservation and promotion of biodiversity in the surrounding area [21], [22].

Vauban is another relatively compact, sustainable neighborhood development located on the southern edge of the city of Freiburg, in Germany. Redeveloped on a former military base, Vauban is largely residential, designed to meet rising housing demand [21]. It is connected by a light rail, providing residents with a short commute to the city center and is virtually car free, with limited parking provided at each house and full walking and cycling orientation. The development is renowned for its passive and active integrative solar design onsite, biomass co-generation plant, integration of nature and car-free or shared-zone streets. The houses are also surrounded by plants and gardens designed and built between 1995 and 2008, with considerable community consultation; this development demonstrates what is possible when citizens and residents are involved and empowered through the planning process.

Vauban is often referred to as an eco-village, sustainable urban district or 'model sustainable neighborhood' [23]. While it does not make any specific carbon claim, studies have shown that Vauban has reduced carbon [20], noting that Vauban residents produce around 0.5 tons CO2/per person/year compared to the average 8.5 tons CO2/per person/year for typical Freiburg residents. The list of initiatives below offers insight into how they were able to achieve this.

Vauban's low-carbon features include the following:

- energy-efficient houses (with all buildings meeting at least the low-energy standard, though 200 are passive houses/units and 59 Energy-Plus houses);
- expansive solar photovoltaic systems on roofs of houses, public and commercial buildings and car parks;
- biomass-fuelled co-generation plant (together with solar supplying 25% of districts electricity needs);
- heavily restricted car parking facilities deterring car ownership (with only 16% of Vauban residents owning a car);
- a mix of car-free and shared-zone streets (with the majority of travel being by foot or bike);
- light-rail connection to the city;
- adoption of housing cooperatives and associations, which allows residents to have responsibility for the management of their building, and thereby increases their awareness around issues such as energy consumption; and
- mixed-use development (around 600 jobs and 5000 residents).

While it is unclear which measures were included in the carbon footprint, it is likely that the low-per capita footprint would be largely attributable to the buildings in Vauban - all of which meet high energy efficiency standards. Although the houses are extremely energy efficient from an operational perspective, it is unclear whether the embodied emissions in materials used in the construction of the buildings have been accounted for this result. Another reason for the low-carbon footprint in Vauban would be related to the energy system supplying the precinct's electricity. Described by Williams (2012) [20] as low or zero-energy system (LZE), co-generation using biomass and solar photo - voltaics supplies one quarter of the district's electricity.

B001 is an eco-development built in the Western Harbor district of Malmo in Southern Sweden. It is a mixed-use, high-density precinct, currently home to 3000 residents as well as some light rail, commercial and tourism businesses. By 2020, the development is anticipated to house between 15 000 and 20 000 residents and attract several eco-businesses to the district [20].

It was previously an industrial precinct and thus in need of decontamination renewal. It is now a popular and attractive residential and tourist location.

B001 is most often cited as an eco-district, but has also been labelled as carbon neutral, climate neutral and energy neutral [24]. Interestingly, there appears to be little information about, or comparison of, the residents' carbon footprints, which seems to be a common metric used by other eco-developments. Most literature on B001 discusses the various initiatives in place, particularly focusing on the energy efficiency standards of the buildings and the low-carbon energy system employed [20].

Some of the low-carbon initiatives implemented at B001 include the following:

- 100% locally generated sustainable energy;
- a wind turbine in the harbor, 3 km from the development, supplying energy to houses;
- solar PV embedded into the development;
- green roofs;
- heating/cooling systems using a local aquifer as storage;
- high energy efficiency standards of buildings (105 kW/m2); and
- a waste to energy system.

Hammarby Sjostad is a 200-ha site located in a close proximity to the city center of Stockholm. Previously contaminated municipality-owned land with poor transport connectivity, Hammarby Sjostad has now become a vibrant, desirable and celebrated eco-district within Stockholm. The district houses 20,000 residents in a relatively dense area (50 units/ha) and boasts one of the most celebrated and discussed 'closed-loop' systems for integrating energy, water, waste and transport at the local level. This has contributed considerably to the reduction in the district's emissions, and Hammarby's prime location (waterfront and close to the city) has been optimized by the extension of a light rail to the development. Hammarby Sjostad is known as an 'eco-district' with its eco-claim predominantly centered on its innovative eco-cycle model or closed-loop resource management system. The development sets the goal of reducing per capita emissions to 2.5–3 tons CO2/per person/year compared with the average Stockholm citizen's emissions of 4 tons CO2/per person/year [20].

Some of the low-carbon initiatives implemented in Hammarby Sjostad include the following:

- a closed-loop system that utilizes the waste products from various processes such as waste water and municipal solid waste to create energy (biofuel, biogas and waste heat), which is used for electricity generation, district heating and fuel in cars;
- micro-generation, i.e., from solar PVs and solar collectors;
- energy-efficient buildings;
- vacuum waste collection;
- light rail connected to city;
- a car share scheme; and
- an Environmental Advice Centre to inform and educate residents about living a low-carbon lifestyle [25].

As Stockholm residents already have one of the lowest per capita carbon foot-prints for a developed city (largely

because of the low-carbon energy grid, district heating network supported by relatively high density, and thermally efficient buildings), it was difficult to find and implement further reduction measures.
All of these examples (BedZED-UK, Vauban, Freiburg-Germany and Hammarby Sjostad, Stockholm-Sweden) are described in detail in the book [26].

4. CONCLUSION

Given that 70% of total GHG emissions come from cities, they are becoming places where action is inevitable in the fight against climate change. Some of the possibilities for reducing CO_2 emissions, as the most widespread greenhouse gas emitted by human activities, are: improving energy efficiency in buildings, which today are responsible for 40% of energy consumption, greater use of renewable energy sources, maintaining mobility, because traffic is responsible for about a quarter of EU GHG emissions, the use of the circular economy, the use of the smart city concept, increasing the capacity of the bio-economy, agriculture and forestry, as well as the implementation of carbon sinks.

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REFERENCES

[1] https://www.europarl.europa.eu/RegistreWeb/search/simple.htm?references=COM_COM(2016)0860&searchLanguages=EN&sortAndOrder=DATE_DOCU_DESC
[2] UN2018 revision of world urbanization prospects, Population Division of the United Nations Department of Economic and Social Affairs (UN DESA) (2018)
[3] ECA Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy Communication from the Commission of the European Parliament (2018)
[4] R. M. Pulselli, S. Broersma, C. Lee Martin, G. Keeffe, S. Bastianoni, A. den Dobbelsteen, "Future city visions. The energy transition towards carbon-neutrality: lessons learned from the case of Roeselare, Belgium", Renewable and Sustainable Energy Reviews, Volume 137, 2021, pp.110612
[5] https://www.c40.org/why_cities accessed on Feb. 01, 2021.
[6] GLADraft London Environment Strategy https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/draft-london-environment-strategy, accessed on February 02, 2021.
[7] U.N. Habitat UN Habitat for a better urban future - climate change (2017), accessed on Feb. 02, 2021., https://unhabitat.org/urban-themes/climate-change/
[8] OECD/IEA Energy Technology Perspective 2016 - towards Sustainable Urban Energy System, Paris ms, 2016.
[9] Close D. Dodman, G. Mc Granahan, B. Dalal-Clayton, "Integrating the Environment in Urban Planning and Management. Key Principles and Approaches for Cities in the 21st Century", 2013
[10] World Economic Forum Inspiring Future Cities and Urban Services Shaping the Future of Urban Development and Services Initiative, 2016
[11] D.Reckien, J. Flacke, R.J. Dawson, O. Heidrich, M. Olazabal, A. Foley, J.J.-P. Hamann, H. Orru, M. Salvia, S. De Gregorio Hurtado, D. Geneletti, F. Pietrapertosa, "Climate change response in Europe: what's the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries", Clim. Change, 122 (2014), pp. 331-340
[12] R. M. Pulselli, S. Broersma, C. L. Martin, G. Keeffe, S. Bastianoni, A. den Dobbelsteen, "Future city visions. The energy transition towards carbon-neutrality: lessons learned from the case of Roeselare, Belgium", Renewable and Sustainable Energy Reviews, Volume 137, 2021, 110612
[13] Covenant of Mayors Office Covenant of Mayors for Climate & Energy, http://www.covenantofmayors.eu/ accessed on February 01, 2021.
[14] Global Covenant of Mayors for Climate and Energy, https://www.globalcovenantofmayors.org/, accessed on February 01, 2021.
[15] Close C40 Cities Climate Leadership GroupC40 Cities Climate Leadership Group, http://www.c40.org, accessed on February 01, 2021.
[16] A. Hobley, "Will gas be gone in the United Kingdom (UK) by 2050? An impact assessment of urban heat decarbonisation and low emission vehicle uptake on future UK energy system scenarios", Renewable Energy, Volume 142, 2019, pp. 695-705
[17] F.Jalil-Vega, I. G. Kerdan, A. D.Hawkes: "Spatially-resolved urban energy systems model to study decarbonisation pathways for energy services in cities", Applied Energy, Volume 262, 2020, pp. 114445
[18] W. Horan, S. Byrne, R. Shawe, R. Moles, B. O'Regan: "A geospatial assessment of the rooftop decarbonisation potential of industrial and commercial zoned buildings: An example of Irish cities and regions", Sustainable Energy Technologies and Assessments, Volume 38, 2020, pp. 100651
[19] J. Hodge, J. Haltrecht, "BedZED Seven years on: The impact of the UK's best known Eco-village and its residents", BioRegional, 2009
[20] J.Williams, "Zero carbon homes: A road map", New York: Earthscan, 2012
[21] P. Newman, I. Jennings,"Cities as sustainable ecosystems: Principles and practices", Washington, DC: Island Press, 2008
[22] P. Newman, T. Beatley, H. Boyer, "Resilient cities: Responding to peak oil and climate change", Washington, DC: Island Press, 2009.
[23] P. Newman, I. Jennings,"Cities as sustainable ecosystems: Principles and practices", Washington, DC: Island Press, 2008.

[24] The Oresund Committee. (2009). The Öresund Region—A growth center for environmental technology. http://www.kooperation-international.de/fileadmin/public/cluster/Kopenhagen/klimatbroschyrENweb.pdf.
[25] K.Takahashi, T. Onishi, "Moves in Europe toward the creation of low-carbon cities", T. Onishi & H. Kobayashi (Eds.), Low carbon Cities: The future of urban planning. Kyoto: Gakugei Shuppan-Sha Co., Ltd. (2011)
[26] V. Rauland, P. Newman, "Decarbonising Cities Mainstreaming Low Carbon Urban Development"

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