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PREFACE

It is our great pleasure to present this Special Issue of the Tehnički glasnik-Technical Journal, which marks the latest chapter in the fruitful collaboration between the Faculty of Mechanical Engineering and Naval Architecture, CAPLM, and the Tehnički glasnik-Technical Journal, a partnership that has continued since 2020. This issue is the third in a series of Special Issues dedicated to the International Scientific Conference "Management of Technology – Step to Sustainable Production" (MOTSP), which has been organized annually since 2009.

The 16th MOTSP Conference takes place from June 3 to June 6, 2025, at the Hotel Miramare in Crikvenica, Croatia. This year's Special Issue features 29 rigorously reviewed papers authored by researchers from eight countries: Austria, Germany, Hungary, Poland, Slovenia, Slovakia, Serbia, and Croatia. The breadth and diversity of these contributions reflect the international character and scientific excellence fostered by the MOTSP community. Additional accepted papers will be published in forthcoming regular issues of the Tehnički glasnik-Technical Journal.

The MOTSP2025 conference featured three invited lectures from leading experts:

- Filip Šuligoj, "Advancements in Robotically Assisted Medical Procedures"
- Sven Maričić, "Application of Artificial Intelligence in Additive Technologies: Case Studies in Robotics and Medicine"
- Tomislav Staroveški, "Innovations in Robotic Sanding and Polishing Systems"

The presented works, delivered through oral presentations and posters, span a wide array of contemporary topics, including but not limited to: digital manufacturing, robotics, artificial intelligence, sustainable production, materials engineering, industrial engineering, industry 4.0/5.0 and industrial process optimization. The papers are organized into thematic sections to facilitate focused discussion and knowledge exchange.

Beyond the scientific content, this issue underscores the MOTSP conference's role as a platform for fostering international collaboration and professional networking. The conference has repeatedly proven to be a catalyst for new partnerships and interdisciplinary research, as exemplified by the ongoing collaboration between researchers from Croatia and India, initiated at MOTSP2024 in Dubrovnik.

We extend our sincere gratitude to all authors, reviewers, and members of the organizing and editorial committees whose dedication and expertise have made this Special Issue possible. We are confident that the contributions collected here will stimulate further research, innovation, and collaboration within the engineering and technology community.

We wish all readers an inspiring and productive engagement with the work presented in this Special Issue.

Dr. Predrag Ćosić, Full Professor with Tenure
Chairman of MOTSP 2025 - Guest Editor

Dr. Zdenka Keran, Associated Professor
Secretary of MOTSP2025

Dr. Milan Kljajin, Full Professor with Tenure
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Reproducibility of Areal Topography Parameters Obtained by Atomic Force Microscope

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Abstract: In the context of quality management and Industry 5.0, reproducibility is a critical indicator of the ability to achieve consistent and predictable results in laboratories, research, as well as in systems and processes. Reproducibility is also an indispensable component of measurement uncertainty, which quantifies the precision of measurement results. To standardize the measurement procedure for surface topography parameters obtained using atomic force microscope (AFM) and to establish the accuracy and precision of measurement results, an analysis of repeatability and reproducibility was conducted in accordance with the ISO 5725-2:2019 standard, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method. Measurements were performed on two AFM standards and a steel sample. The research was conducted over the course of one year and repeated after four years using the same samples.

Keywords: areal topography parameters; atomic force microscope; Industry 5.0; quality management; reproducibility

1 INTRODUCTION

In the contemporary context of quality management and the development of Industry 5.0, the reproducibility of measurement results represents a critical parameter for ensuring consistency and predictability across various domains of scientific research, laboratory testing, and complex industrial and technological systems. The reproducibility of measurement results has become to be a fundamental aspect of quality management in diverse industries, particularly during the transition to Industry 5.0, where human-machine collaboration and advanced technologies are take center stage.

International standards such as ISO 5725 – Accuracy (trueness and precision) of measurement methods and results [1] and ISO 21748:2017 – Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty evaluation [2] provide guidelines for assessing the accuracy and precision (repeatability, reproducibility) of measurement methods. Accurate and precise measurement data are crucial for implementing technologies such as IoT and big data analytics in Industry 4.0. These standards also offer a framework for evaluating and managing measurement uncertainty, ensuring high-quality standards in personalized manufacturing characteristic of Industry 5.0. Integrating ISO 5725 and ISO 21748:2017 into measurement processes ensures that decisions are based on accurate, reliable, and comparable data, which is essential for successful business operations and research. The analysis of repeatability and reproducibility in accordance with ISO 5275 is conducted across various fields and branches of science, including measurement system analysis [3], chemistry [4], medicine [5] and others.

Surface topography as one of the main indicators of surface quality plays a key role in determining the mechanical, tribological, biological, optical and other product properties [6]. The development of technologies has increased the requirements for surface quality, and thus the need for three-dimensional (areal) measurement techniques and surface characterization [7]. Surface topography testing is performed using different methods and a wide array of linear and areal topography parameters [8]. The first devices for measuring the topography, i.e. the roughness of the technical surface were stylus instruments, and they were developed in the 1930s [9]. The surface topography test using a stylus instrument with a probe is carried out by means of the probe tip, which makes contact with the tested surface and moves along the direction of measurement. With a stylus instrument, line (2D) profile measurement is performed, which provides some functional data on the surface. However, areal or three-dimensional (3D) measurement is required to fully characterize functional surface information [10]. The development of the white light interferometer and the 3D non-contact profilometer in the early 1980s enabled areal measurement of surface topography [11]. The non-contact profilometer, operating on the principle of light interference, is currently the most commonly used optical device. Today, due to increasingly stringent surface quality requirements, surface topography testing is also conducted using scanning microscopes, in addition to the traditional methods mentioned above. Scanning microscopes, in order to obtain information on surface topography, are divided into scanning electron microscopes and microscopes with scanning probes. The scanning electron microscope operates by directing an electron beam focused by an electromagnetic field. Microscopes with scanning probes create an image of the surface by using a probe that touches the surface for data collection [12]. Among microscopes with scanning probes, the atomic force microscope (AFM) stands out, enabling the display of surface topography in both 2D and 3D.

It can be concluded that today numerous methods and instruments have been developed that are used for testing and analysis of surface topography [13]. All these methods, both traditional and modern, require clear protocols for the calibration of measuring instruments and internationally recognized standards that define measurement conditions, criteria for input values in measurement procedures, parameters that characterize the surface, procedures for evaluating measurement uncertainty, and so on. These methods rely on entirely different measurement principles, so without a clearly defined instrument calibration procedure, measurement procedure, and result analysis, achieving compatibility between results obtained from different methods is unlikely. There are a large number of standards in the field of surface topography measurement, and new standards are currently under development. The aim of these developing standards is to achieve harmonization in the field of surface topography measurement. The objective of this study is to determine the stability (repeatability and reproducibility) of measurement results obtained by AFM in the field of surface topography.

2 AREAL TOPOGRAPHY PARAMETERS

Surface topography is a three-dimensional characteristics of a surface that provides a quantitative insight into the condition of the surface, and includes components of surface texture (roughness and waviness) and other irregularities, such as deviations from the shape [14].

The parameters describing surface topography can be categorized into line (2D) and areal (3D) parameters. Line parameters are derived from data collected along a single line, based on the surface profile. Depending on the type of profile, the line parameters can be designated as *P* for primary profile, *W* for waviness profile, and *R* for roughness profile. According to the ISO 4287:1997 standard, "Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters," line roughness parameters are classified into four main groups: amplitude, spacing, hybrid, and curve-related parameters.

Areal topography parameters quantitatively describe the condition of the surface of the measured sample and are designated as marked *S* or *V* [3]. Parameters marked with the label *S* describe the scanned area, while those labeled *V* indicate the material volume per unit area [15]. These are commonly referred to as 3D topography or roughness parameters in the literature. Unlike line parameters, the initial letter of the surface parameter label does not indicate the type of surface observed (roughness or waviness). For example, the parameter *Sa* can be applied to roughness, waviness, or primary profile data [3]. In order to unambiguously interpret the results, it is necessary to indicate which filter was used next to the areal topography parameter. To unambiguously interpret the results, it is important to specify the filter used alongside the areal topography parameter.

Table 1 Areal topography parameters

Arithmetical mean height	$Sa = \sqrt{\frac{1}{A}\iint_A \lvert z(x,y) \rvert \mathrm{d}x\mathrm{d}y}$
Root mean square height	$Sq = \sqrt{\frac{1}{A}\iint_A \lvert z^2(x,y) \rvert \mathrm{d}x\mathrm{d}y}$
Maximum height	*Sz*

There are numerous surface topography parameters that are needed to fully describe the surface condition. According to the ISO 25178-2:2021 standard, Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameter [16], areal topography parameters are grouped into several categories: height, spatial, hybrid, functional, related, and miscellaneous parameters. To gain a comprehensive understanding of the surface's condition, it is essential to monitor as many areal topography parameters as possible. Tab. 1 provides the expressions used to calculate the areal surface topography parameters measured in this study.

3 REPEATABILITY AND REPRODUCIBILITY OF MEASUREMENT RESULTS

The paper analyses the repeatability and reproducibility of areal topography parameters *Sa*, *Sq* and *Sz* obtained by the atomic force microscope (Oxford MFP-3D Origin). Prior to conducting the measurements, the AFM was calibrated using the STS3-1000P standard, developed by the American company VLSI Standards. The selected scan size is 20 µm × 20 µm, the scan resolution is 256, and the scan speed is 80 µm s^{-1}. Areal topography parameters *Sa*, *Sq* and *Sz* measured by the atomic force microscope were measured on the primary surface, i.e. they were not filtered. Measurements were performed on two AFM standards and a steel sample. The standards and sample are presented in 2D and 3D view in Figs. 1, 2 and 3.

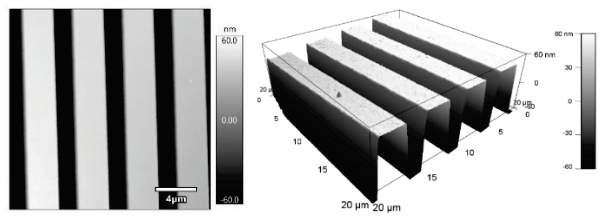

Figure 1 Standard 1 in two-dimensional and three-dimensional form

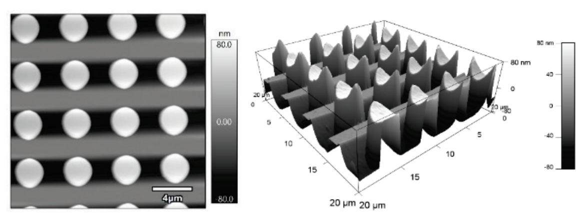

Figure 2 Standard 2 in two-dimensional and three-dimensional form

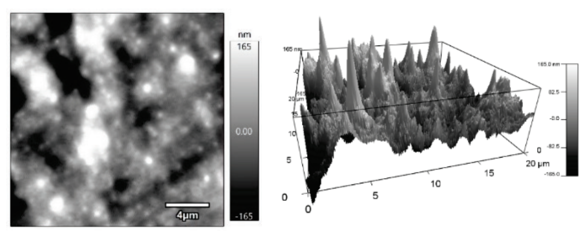

Figure 3 Sample in two-dimensional and three-dimensional form

The calculation of repeatability and reproducibility of measurement results was performed in accordance with ISO 5725-2:2019 standard, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method [17]. Definitions of basic terms and expressions for the calculation of repeatability and reproducibility in accordance with ISO 5725-2:2019 are provided in Tab. 2. In accordance with ISO 5725 standard, repeatability and reproducibility are assessed on the basis of comparative measurements between laboratories. In this paper, the theory of comparative measurements is applied to measurements within one laboratory. The term laboratory has been replaced by the term measuring series, and refers to a change in the measurement conditions (e.g. a change in the measuring point on a standard or object of measurement). The analysis was performed to determine the precision and compatibility of measuring devices and methods.

Table 2 Definitions of basic terms and expressions

Repeatability Precision under repeatability conditions. Conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time.	
Reproducibility Precision under reproducibility conditions. Conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment.	
Terms	Expressions (Formulae)
The arithmetic mean of test results x_{ij} in the i^{th} measurement series. n – number of repeated measurements Index i represents the measurement series (i = 1, 2, ... m) Index j represents the measurement in the measurement series (j = 1, 2, ... n)	$\bar{x}_i = \frac{1}{n_i}\sum_{j=1}^{n} x_{ij}$
Grand mean of test results N – total number of measurements	$\bar{x} = \frac{1}{N}\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}$
The estimate of the within-measurement series standard deviation.	$s_i = \sqrt{\frac{\sum_{j=1}^{n}(x_i - \bar{x})^2}{n_i - 1}}$
Repeatability standard deviation	$s_r = \sqrt{\frac{\sum_{i=1}^{m}(n_i - 1)s_i^2}{\sum_{i=1}^{m} n_i - 1}}$
The estimate of the between-measurement series standard deviation.	$s_L = \sqrt{s_d^2 - \frac{s_r^2}{n}}$
The estimate of the standard deviation of the mean of measurement series	$s_d = \sqrt{\frac{\sum_{i=1}^{m}(\bar{x}_i - \bar{\bar{x}})^2}{m-1}}$
Reproducibility standard deviation	$s_R = \sqrt{s_r^2 + s_L^2}$
Repeatability limit – with a probability of 95 %.	$r = 2.8 s_r$
Reproducibility limit – with a probability of 95 %.	$R = 2.8 s_R$

In order to calculate the repeatability and reproducibility of areal topography parameters *Sa*, *Sz* and *Sq*, 15 repeated measurements were performed on the standards in two measurement series. Within the measurement series, measurements were performed under repeatability conditions (same metrologies, same measuring instrument, same measurement conditions, repeating measurements in a short period of time). Between the measurements performed in the first and second measurement series (measurements performed in two days), the repeatability conditions were not fully met, but the reproducibility conditions were entered.

In order to examine the influence of surface quality (uniformity) on the reproducibility of areal parameters of surface topography, measurements were performed on standards and steel sample. Measurements were performed in five measuring series (different measuring points) with three repeated measurements. The term different measuring points refers to three repeated measurements performed at five distinct locations on a single standard or sample. The conducted statistical tests did not reveal outliers in the measurement results.

The comparison of results was conducted using the *En* agreement factor (Eq. (1)), where *n* represents the number of laboratories participating in the study.

$$En = \frac{|\bar{x}_1 - \bar{x}_2|}{2\sqrt{u_1^2 + u_2^2}} \le 1 \quad (1)$$

The measurement uncertainties of areal topography parameters were evaluated by mathematical models in [15], and are eaqual to $u(Sa)$ = 2.2 nm, $u(Sz)$ = 3.5 nm, $u(Sq)$ = 2.4 nm.

4 ANALYSIS OF MEASUREMENT RESULTS

The analysis results of repeatability and reproducibility of areal topography parameters *Sa*, *Sz* and *Sq* performed on standards in two measurement series of which each contained fifteen repeated measurements. Results are shown in Tables 3 and 4. The measured values of repeatability *r* and reproducibility *R* are the values within which it can be expected that there is a difference between two individual measurement results, obtained under the conditions of repeatability and reproducibility with probability *P*. The tables present the results measured in 2021 and four years later, in 2025.

Table 3 Standard 1 – two measurement series

	Sa/nm		*Sz*/nm		*Sq*/nm	
2021	Measurement series		Measurement series		Measurement series	
	1	2	1	2	1	2
$\bar{x}$	50.85	50.16	174.52	175.91	54.65	54.39
s_i	0.15	0.22	1.40	1.59	0.47	0.20
$\bar{\bar{x}}$	50.50		175.22		54.52	
r	0.528		4.133		0.995	
R	0.567		4.433		1.027	
2025	Measurement series		Measurement series		Measurement series	
	1	2	1	2	1	2
$\bar{x}$	50.24	51.24	182.50	176.63	51.812	53.71
s_i	0.16	0.19	2.03	1.63	0.174	0.244
$\bar{\bar{x}}$	50.74		179.63		52.76	
r	0.489		5.094		0.586	
R	0.593		5.394		0.881	
En	0.04		0.44		0.26	

The absolute difference of two individual measurement results of parameters *Sa*, *Sz* and *Sq*, under repeatability and reproducibility conditions will in no more than 5 % of cases be greater than *r* and *R*. For example: The absolute difference of two individual measurement results of parameters *Sa* and *Sq* under reproducibility conditions will in no more than 5 % of cases be greater than 1 nm. The absolute difference of two individual measurement results of parameters *Sz* under reproducibility conditions will in no more than 5 % of cases be greater than 6 nm. The results showed that by repeating the measurements after a long period of time we did not enter the reproducibility conditions, ie that the time period between measurements does not significantly affect the areal topography parameters *Sa*, *Sz* and *Sq*.

Table 4 Standard 2 – two measurement series

	Sa/nm		*Sz*/nm		*Sq*/nm	
2021	Measurement series		Measurement series		Measurement series	
	1	2	1	2	1	2
$\bar{x}$	28.87	28.28	205.54	203.21	40.61	40.00
s_i	0.17	0.17	1.27	1.68	0.17	0.18
$\bar{\bar{x}}$	28.57		204.37		40.30	
r	0.468		4.114		0.477	
R	0.498		4.114		0.509	
2025	Measurement series		Measurement series		Measurement series	
	1	2	1	2	1	2
$\bar{x}$	30.88	30.69	205.30	210.03	41.52	41.811
s_i	0.28	0.12	1.42	1.98	0.28	0.12
$\bar{\bar{x}}$	30.79		207.67		41.67	
r	0.592		4.763		0.595	
R	0.592		4.902		0.595	
En	0.36		0.33		0.21	

Table 5 Standard 1 – five measurement series (*Sa*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	51.24	51.59	52.38	51.5	50.99
s_i	0.03	0.08	0.06	0.03	0.06
$\bar{\bar{x}}$	51.54				
r	0.148				
R	1.460				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	50.47	49.73	51.45	52.08	51.78
s_i	0.17	0.05	0.05	0.08	0.05
$\bar{\bar{x}}$	51.10				
r	0.257				
R	2.711				
En	0.07				

Table 6 Standard 1 – five measurement series (*Sz*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	198.3	159.9	170.1	189.1	173.2
s_i	1.00	0.79	0.25	1.12	1.17
$\bar{\bar{x}}$	178.20				
r	2.572				
R	24.616				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	140.09	191.49	215.10	173.31	163.63
s_i	3.12	1.25	2.61	4.40	1.01
$\bar{\bar{x}}$	176.72				
r	3.664				
R	29.665				
En	0.15				

The analysis of the results of repeatability and reproducibility of areal topography parameters *Sa*, *Sz* and *Sq* were performed on standards in a set of five measurement series of which each contained three repeated measurements. Results are shown in tables 5 to 10.

The analysis was conducted to determine the impact of surface quality (uniformity) on reproducibility of areal topography parameters.

The results showed that the change of the measuring point on the standards does not significantly affect the areal topography parameters *Sa* and *Sq*. The absolute difference of two individual measurement results of parameters *Sa* and *Sq* under reproducibility conditions will in no more than 5 % of cases be greater than 1 nm.

Table 7 Standard 1 – five measurement series (*Sq*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	54.29	54.66	55.12	54.64	54.27
s_i	0.03	0.07	0.08	0.06	0.07
$\bar{\bar{x}}$	54.59				
r	0.180				
R	0.971				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	53.54	53.70	55.08	55.18	54.17
s_i	0.14	0.11	0.11	0.21	0.18
$\bar{\bar{x}}$	54.34				
r	0.423				
R	2.134				
En	0.04				

Table 8 Standard 2 – five measurement series (*Sa*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	28.69	29.34	29.7	28.69	28.61
s_i	0.02	0.06	0.03	0.04	0.02
$\bar{\bar{x}}$	29.01				
r	0.106				
R	0.786				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	30.49	30.98	31.11	30.86	30.14
s_i	0.11	0.11	0.19	0.24	0.29
$\bar{\bar{x}}$	30.71				
r	0.558				
R	1.183				
En	0.24				

Table 9 Standard 2 – five measurement series (*Sz*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	198.3	205.4	209.3	203.6	203.8
s_i	0.20	0.26	0.26	0.29	0.12
$\bar{\bar{x}}$	204.11				
r	0.644				
R	6.343				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	242.96	293.54	212.61	190.67	188.74
s_i	0.43	0.37	0.40	0.26	0.29
$\bar{\bar{x}}$	205.7				
r	0.986				
R	23.879				
En	0.16				

The change of the measuring point on the standard 2 introduced the conditions of reproducibility, ie the change of the measuring point significantly effects the areal topography parameter *Sz*. The absolute difference of two individual measurement results of parameter *Sz* under reproducibility conditions will in no more than 5 % of cases be greater than 25 nm.

The analysis results of repeatability and reproducibility of areal topography parameters *Sa*, *Sz* and *Sq* were performed on sample in five measurement series of which each contained three repeated measurements. Due to its irregular surface, the measurement uncertainty of the topography parameters is higher than that of the reference standards. Results are shown in Tabs. 11 to 13.

Table 10 Standard 2 – five measurement series (*Sq*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	40.07	39.56	39.53	39.46	40.37
s_i	0.04	0.02	0.01	0.03	0.03
$\bar{\bar{x}}$	39.80				
r	0.077				
R	1.111				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	41.30	41.78	41.82	41.64	41.52
s_i	0.16	0.11	0.08	0.17	0.13
$\bar{\bar{x}}$	41.61				
r	0.368				
R	0.654				
En	0.27				

Table 11 Sample – five measurement series (*Sa*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	62.84	124.3	111.7	90.7	102.1
s_i	0.35	0.49	1.49	0.18	1.01
$\bar{\bar{x}}$	98.33				
r	2.362				
R	64.635				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	104.85	93.60	80.64	97.80	112.33
s_i	0.28	0.20	1.24	0.75	1.61
$\bar{\bar{x}}$	97.85				
r	2.711				
R	33.148				
En	0.08				

Table 12 Sample – five measurement series (*Sz*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	749.42	992.88	1020.85	757.35	01247.12
s_i	0.40	14.41	21.48	3.08	3.72
$\bar{\bar{x}}$	913.52				
r	32.521				
R	408,40				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	1101.07	722.90	650.18	816.32	1164.33
s_i	9.50	5.83	3.52	16.31	8.16
$\bar{\bar{x}}$	890.96				
r	26.772				
R	634.61				
En	0.97				

Based on the analysis of repeatability *r* and reproducibility *R* performed on the sample, it can be concluded that the change of the measuring point on the sample introduced the conditions of reproducibility, i.e. that the change of the measuring point significantly effects the areal topography parameters.

According to the ISO 21748: 2017 standard, Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty evaluation [2], one of the input values in the mathematical model for evaluating measurement uncertainty is the reproducibility of measurement results. The standard deviation s_R is expected to be estimated from comparative measurements. In this paper, the theory of comparative measurements is applied to measurements within one laboratory, and the term different laboratories refers to a change in the measurement conditions (e.g. change of the measuring point on the object of measurement).

Table 13 Sample – five measurement series (*Sq*/nm)

2021	Measurement series				
	1	2	3	4	5
$\bar{x}$	83.93	173.3	145.9	113.2	102.8
s_i	0.3	0.81	1.74	0.08	2.95
$\bar{\bar{x}}$	123.82				
r	4.359				
R	35.659				
2025	Measurement series				
	1	2	3	4	5
$\bar{x}$	129.60	118.71	101.72	123.03	132.56
s_i	0.19	0.14	1.09	0.63	1.33
$\bar{\bar{x}}$	121.12				
r	2.278				
R	33.578				
En	0.40				

The difference in repeatability and reproducibility values before and after four years for measurements of two measurement series across all measured parameters is less than 1 nm. For measurements of five measurement series on Standards 1 and 2, the difference in repeatability and reproducibility before and after four years is less than 2 nm for the *Sa* and *Sq* parameters and less than 4 nm for the *Sz* parameter. The values of the *En* agreement factor for all measurements on Standards 1 and 2 before and after four years are less than 1, indicating that the results are compatible. Differences in repeatability and reproducibility before and after four years for the measurement sample, can be attributed to the non-uniform surface of the measurement sample.

5 CONCLUSION

Ensuring high repeatability and reproducibility of measurement results is a fundamental prerequisite for effective quality management and the advancement of Industry 5.0. Reliable measurement data are essential for integrating advanced manufacturing technologies, including artificial intelligence-driven quality control, cyber-physical systems, and data-driven process optimization. The principles of ISO 5725 and ISO 21748 provide a robust framework for evaluating measurement accuracy and precision, supporting enhanced decision-making in intelligent manufacturing ecosystems. The increasing reliance on digitalization and automation in Industry 5.0 underscores the need for standardized measurement methodologies to ensure process stability, minimize variability, and achieve high precision in next-generation manufacturing and research environments.

This study applied the theory of comparative measurements to the assessment of surface topography parameters in accordance with ISO 5725:2019. The repeatability and reproducibility of the areal topography parameters *Sa*, *Sz*, and *Sq* obtained using an atomic force microscope were analyzed on two reference standards and one sample.

The analysis of measurement series conducted over a four-year interval demonstrated a high degree of consistency in results. Differences in repeatability and reproducibility values before and after four years for two measurement series were below 1 nm, while for five series performed on Reference Standards 1 and 2, they remained below 2 nm for parameters *Sa* and *Sq*, and below 4 nm for *Sz*. The *En* agreement factor, remaining below 1, confirms the long-term stability of the measurement system. However, for the measurement sample, the *En* agreement factor close to 1 suggest that variations can be attributed to the non-uniformity of the sample surface.

Furthermore, the change of the measuring point on the reference standards did not significantly affect the results for *Sa* and *Sq*, while *Sz* exhibited notable dependence. The observed differences in measurements obtained with a time lag were attributed to random variability, reinforcing system stability. However, on the sample, the variation of the measuring point introduced reproducibility conditions, significantly influencing the measured areal topography parameters.

6 REFERENCES

[1] International Organization for Standardization. (2023). *ISO 5725-1:2023(en), Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions*

[2] International Organization for Standardization. (2017). *ISO 21748:2017 Guidance for the use of repeatability, reproducibility and trueness estimates in measurement uncertainty evaluation*.

[3] D'Aucelli, G. M., Giaquinto, N., Mannatrizio, S., & Savino, M. (2017). A fully customizable MATLAB framework for MSA based on ISO 5725 standard. *Measurement Science and Technology, 28*(4), 044007. https://doi.org/10.1088/1361-6501/aa542f

[4] Canas, S., Assunção, M., Brazão, J., Zanol, G., & Eiras-Dias, J. E. (2015). Phenolic compounds involved in grafting incompatibility of *Vitis* spp: Development and validation of an analytical method for their quantification. *Phytochemical Analysis, 26*(1), 1-7. https://doi.org/10.1002/pca.2526

[5] Kim, J., Lee, K. H., Kim, J., Shin, Y. J., & Lee, K. W. (2019). Improved repeatability of subsolid nodule measurement in low-dose lung screening with monoenergetic images: A phantom study. *Quantitative Imaging in Medicine and Surgery, 9*(2), 171-179. https://doi.org/10.21037/qims.2018.10.06

[6] Niemczewska-Wójcik, M. (2017). Wear mechanisms and surface topography of artificial hip joint components at the subsequent stages of tribological tests. *Measurement, 107*, 89–98. https://doi.org/10.1016/j.measurement.2017.04.045

[7] Qu, S., Gong, Y., Yang, Y., Cai, M., & Sun, Y. (2018). Surface topography and roughness of silicon carbide ceramic matrix composites. *Ceramics International, 44*(12), 14742-4753. https://doi.org/10.1016/j.ceramint.2018.05.104

[8] Razumić, A., et al. (2024). Atomic force microscopy: Step height measurement uncertainty evaluation. *Tehnički glasnik, 18*(2), 209-214. https://doi.org/10.31803/tg-20230829155921

[9] Digital Surf. (2021). *Introduction to surface texture - Surface Metrology Guide*. Retrieved from https://guide.digitalsurf.com/en/guide-surface-texture.html

[10] Leach, R. (Ed.). (2011). *Optical measurement of surface topography* (1st ed.). Springer-Verlag Berlin Heidelberg. Retrieved from http://gen.lib.rus.ec/book/index.php?md5=455aa38eb8cedd8998ffec766c15f800

[11] Whitehouse, D. J. (Ed.). (2021). *Handbook of surface and nanometrology*. Routledge & CRC Press. Retrieved from https://www.routledge.com/Handbook-of-Surface-and-Nanometrology/Whitehouse/p/book/9781420082012

[12] Zhang, L., Long, Q., Liu, Y., Zhang, J., & Feng, Z. (2016). Correlation-steered scanning for scanning probe microscopes to overcome thermal drift for ultra-long time scanning. *Ultramicroscopy, 166*, 16-26. https://doi.org/10.1016/j.ultramic.2016.03.013

[13] Leach, R. K., & Hart, A. (2021). A comparison of stylus and optical methods for measuring 2D surface textures. Retrieved from https://eprintspublications.npl.co.uk/2209/

[14] Kumar, B. R., & Rao, T. S. (2012). AFM studies on surface morphology, topography and texture of nanostructured zinc aluminum oxide thin films. *Digest Journal of Nanomaterials and Biostructures, 7*(4), 9.

[15] Razumić, A. (2024). Estimation of measurement uncertainty in the field of atomic force microscopy in dimensional nanometrology. *Doctoral dissertation*, University of Zagreb. Retrieved from https://urn.nsk.hr/urn:nbn:hr:235:432266

[16] International Organization for Standardization. (2021). *ISO 25178-2:2021(en), Geometrical product specifications (GPS) — Surface texture: Areal — Part 2: Terms, definitions and surface texture parameters*.

[17] International Organization for Standardization. (2019). *ISO 5725-2:2019, Accuracy (trueness and precision) of measurement methods and results — Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*.

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Risk Assessment Procedure for Calibration

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Abstract: In the product quality assessment process, it is determined whether the product meets the specified requirements. The assessment is based on measuring the specific characteristics of the product. Depending on the measurement uncertainty, the risk of accepting a product that does not meet specifications can be assessed, i.e., the consumer's risk. Conversely, rejecting a product that meets specifications poses a risk for the manufacturer. The standard method of risk assessment by points has been expanded planar and spatially and was applied for risk calculation during the calibration of the roundness measurement device on a moderate scale from −3 μm to 3 μm. A known observation of the dependent variables is used to calculate the producer's and consumer's risk of the corresponding explanatory variable. The risk of calibration was performed for the linearized tolerance interval. Measurement uncertainty of the calibrated value was determined from the regression line by utilizing the propagation of error.

Keywords: calibration; confusion matrix; consumer's risk; producer's risk; uncertainty

1 INTRODUCTION

1.1 Conformity Assessment, Basic Information

A product's quality assessment implies verification of its compliance with the required standards. The decision about conformity is based on the measured value of one or more characteristics of an item of interest and the measurement uncertainty associated with the provided measurement [1]. However, in the conformity assessment procedure, the wrong decisions can occur [2]. The product may be rejected as non-compliant despite meeting the specified requirements. This poses a risk to the producer and results in a loss of profit. On the other hand, accepting a product that does not conform to specifications is detrimental to the consumer [3].

In this study global producer's risk R_P and global consumer's risk R_C are calculated based on decision rules with a guard band [4]. A guard band of length w is placed between the tolerance interval $[T_L, T_U]$ and the acceptance interval $[A_L, A_U]$. The tolerance interval represents the interval of permissible values for a particular property of an item of interest. It is assumed that the true value of the measurement should be within the tolerance range. Acceptance interval is the interval of permissible measured quantity values [5]. The symbols T_L and A_L refer to the lower limit of the tolerance interval and the acceptance interval, respectively. Analogously, the symbols T_U and A_U are used for the upper limit of the tolerance interval and the acceptance interval, respectively.

The global risk of producers and consumers was estimated using the Bayesian approach [6]. This approach combines prior knowledge of the quantity being measured with information obtained during the measurement process. The true value of measurement is assumed to be unknown. It is therefore modelled as a random variable with assigned the appropriate distribution g_0 with possible values η. The parameters of prior distribution g_0 are the best estimate of the measured quantity y_0 and the measurement uncertainty u_0 associated with the best estimate. The choice of prior depends on the measurand nature. Most often it is a normal distribution, but it can also be some other distribution [7-9]. Measurement data are modelled using the likelihood function h with taking the measurement uncertainty u_m obtained from the measurement process. The likelihood function usually is characterised by a normal distribution [5].

1.2 Regression vs Calibration Models for Risk Assessments

The calibration risk assessment models are based on regression risk assessment models. Depending on the method of calculating measurement uncertainty and the appearance of tolerance and acceptance curves, three models are used to estimate the global producer's and consumer's risk for regression [10]. Concerning the tolerance interval and acceptance interval, linearized and non-linearized models can be defined for risk assessment in regression, that is, calibration. In the linearized model, tolerance and acceptance lines are positioned parallel to the $y = x$ line. Also, tolerance and acceptance lines are placed symmetrically from both sides of the $y = x$ line. The same applies to the tolerance and acceptance curves for the non-linearized model, shown in Fig. 1.

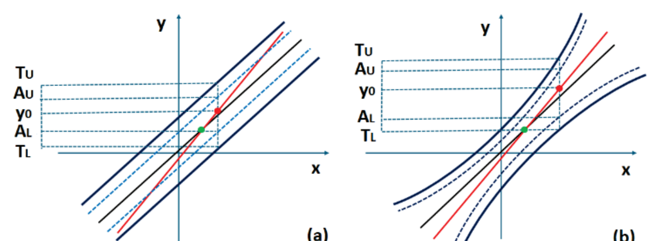

Figure 1 Tolerance and acceptance intervals: a) linearized model; b) non-linearized model [10]

Measurement uncertainty can be determined by using comprehensive measurement performance data or by considering a functional relationship obtained by linear regression analysis [10]. These measurement uncertainties are denoted with u_0^{GUM} and u_0^{LRA}, respectively. The measurement uncertainty u_0^{GUM} is the same for all points of the moderate scale x. On the other hand, measurement uncertainty u_0^{LRA} is calculated according to the propagation of error performed for the equation of regression line.

Therefore, the points of the moderate scale have different measurement uncertainties. The measurement uncertainties calculated in this manner are the largest for points located on the edges of the moderate scale, and the smallest in the middle of the moderate scale [11].

A trivial regression risk assessment model is a model with linearized acceptance and tolerance intervals combined with measurement uncertainty u_0^{GUM}. The non-linearized model is always used in combination with the measurement uncertainty u_0^{LRA}. In that case, the limits of tolerance and acceptance intervals depend on the measurement uncertainty u_0^{LRA} [10]. In this study, the risk assessment procedure for calibration is derived from a linearized regression model in combination with measurement uncertainty u_0^{LRA}.

1.3 Linearized Tolerance and Acceptance Intervals

For the linearized model, tolerance and acceptance lines are set parallel to the $y = x$ line. Let for the points of moderate scale x_i, $i = 1, 2, \ldots, n$ be valid $y_i' = x_i$, where n is the total number of points on a moderate scale, for which measurement was performed. When determining the regression line, the mean of m repeated measurements at the points of the moderate scale was used. The regression line has the form:

$$y = \alpha + \beta x, \tag{1}$$

where β is a slope and α is the y-intercept of the regression line. The values of the regression line y_i calculated at the points of the moderate scale x_i, $i = 1, 2, \ldots, n$ are obtained from the equation:

$$y_i = \alpha + \beta x_i,\ i = 1, 2, \ldots, n. \tag{2}$$

The upper tolerance line is set relative to the $y = x$, and it is given by the equation:

$$T_{\mathrm{U}i} = y_i' + \alpha_{\mathrm{U}},\ i = 1, 2, \ldots, n. \tag{3}$$

Analogously, the lower tolerance line is calculated from the equation:

$$T_{\mathrm{L}i} = y_i' - \alpha_{\mathrm{L}},\ i = 1, 2, \ldots, n. \tag{4}$$

The values α_{U} and α_{L} in Eq. (3) and (4) represent the y-intercept of the upper and lower tolerance lines, respectively. Due to symmetry, it is valid that $\alpha_{\mathrm{U}} = \alpha_{\mathrm{L}} > 0$. The tolerance interval has a range $\Delta T = \alpha_{\mathrm{U}} + \alpha_{\mathrm{L}} = 2\alpha_{\mathrm{U}}$. The acceptance interval may fall within the tolerance interval. If that is the case, then is valid that $[A_{\mathrm{L}}, A_{\mathrm{U}}] \subset [T_{\mathrm{L}}, T_{\mathrm{U}}]$, and holds $A_{\mathrm{L}} = T_{\mathrm{L}} + w$, $A_{\mathrm{U}} = T_{\mathrm{U}} - w$. Likewise, the acceptance interval can exceed the tolerance interval, i.e. it is valid that $[A_{\mathrm{L}}, A_{\mathrm{U}}] \supset [T_{\mathrm{L}}, T_{\mathrm{U}}]$. Then the acceptance interval is $[A_{\mathrm{L}}, A_{\mathrm{U}}] = [T_{\mathrm{L}} - w, T_{\mathrm{U}} + w]$. This is the widest interval along the guard band axis at which the risk curves can be observed. This interval encompasses both the above-mentioned interrelationships between the acceptance interval and tolerance interval, as well as the case when the limits of the tolerance and acceptance intervals coincide. The risk curves along the guard band axis will be shown for the subdivision nodes of the interval $[T_{\mathrm{L}} - w, T_{\mathrm{U}} + w]$. Also, behaviour of risk curves will be presented along a moderate scale.

Calibration risk assessment models are designated from the specified regression risk assessment models. The calibration and regression risks for the linearized model in combination with the measurement uncertainty u_0^{GUM} can be equal. This holds if the measurement uncertainty of the response variable in the regression model $u_{y_{\mathrm{r}}}^{GUM}$ is equal to the measurement uncertainty of the explanatory variable $u_{x_{\mathrm{e}}}^{GUM}$ in the calibration model. Also, the equality of risk in regression and calibration within this model arises from the model's geometry. It is straightforward to demonstrate that, for a given value of the response variable y_{r}, the value of the explanatory variable x_{e}, lies within the tolerance interval $[y_{\mathrm{r}} - \alpha_{\mathrm{U}}, y_{\mathrm{r}} + \alpha_{\mathrm{L}}]$ and holds $|\overline{AB}| = |\overline{CD}| = |\alpha_{\mathrm{U}} + \alpha_{\mathrm{L}}| = 2\alpha_{\mathrm{U}} = \Delta T$, as well as $|\overline{ET}| = |\overline{TF}| = |y_{\mathrm{r}} - x_{\mathrm{e}}|$, Fig. 2. This implies that x_{e} and y_{r} are symmetrically positioned within the segments $\overline{AB}$ and $\overline{CD}$ respectively, in terms of their distances from the endpoints of these segments. In this trivial model, the risks for regression and calibration differ if and only if $u_{y_{\mathrm{r}}}^{GUM} \neq u_{x_{\mathrm{e}}}^{GUM}$.

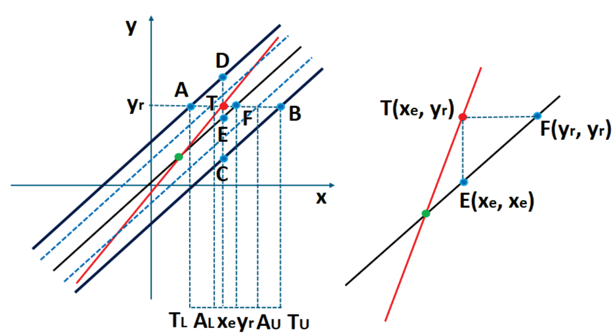

Figure 2 Linearized tolerance and acceptance interval for the explanatory variable

1.4 Measurement Uncertainty for Calibration Models

In the present study, a risk estimation model for calibration was examined, which is derived from a linearized risk estimation model for regression in combination with the measurement uncertainty u_0^{LRA}. The tolerance and acceptance intervals for risk estimation in calibration, in the case where the acceptance interval is contained within the tolerance interval, are modelled as described previously and shown in Fig. 2.

The fundamental difference in risk estimation between regression and calibration lies in the way the measurement uncertainty u_0^{LRA} is calculated. In risk estimation for regression, the measurement uncertainty u_0^{LRA} is computed for the values of the regression line y_i, $i = 1, 2, \ldots, n$ using the equation:

$$u_0^{LRA}(y_i) = \sqrt{u^2(\alpha) + x_i^2 u^2(\beta) + \beta^2 \sigma_x^2}. \quad (5)$$

The measurement uncertainty in the calibration model is calculated for the values of the explanatory variable, i.e., for the points of the moderate scale x_i, where $i = 1, 2, \ldots, n$ using the equation [11]:

$$u_0^{LRA}(x_i) = \sqrt{\frac{\sigma_y^2 + u^2(\alpha)}{\beta^2} + \frac{(y_i - \alpha)^2 u^2(\beta)}{\beta^4}}. \quad (6)$$

Eqs. (5) and (6) apply to a symmetric equidistant moderate scale centered around zero observed in this study. Details on how to calculate the measurement uncertainties $u(\alpha)$, $u(\beta)$ and the quantities σ_x and σ_y can be found in [10].

2 METHODS AND MATERIALS
2.1 Measurement Description

The risk assessment was performed during the calibration of the Mahr MMQ3 roundness measuring device. Data were collected throughout the calibration process of an inductive contact probe (dial indicator) on a universal length measuring machine (ULM). All measurements were conducted at the University of Zagreb in the Laboratory for Precise Measurement of Length at the Faculty of Mechanical Engineering and Naval Architecture. The risk assessment was carried for moderate scale in a range from –3 µm to 3 µm. For each of the $n = 13$ moderate scale points, $m = 3$ measurements were performed, and their mean values were considered [12]. The regression line is given by the equation:

$$y = -0.002784 + 1.008392x. \quad (7)$$

The remaining quantities necessary for calculating the measurement uncertainty u_0^{LRA} from Eq. (6) have the following values: $\sigma_y = 0.0182$ µm, $u(\alpha) = 0.005375$ µm and $u(\beta) = 0.003804$ µm. To overcome detected residuals autocorrelation from Ordinary Least Square regression (OLS), parameters α and β and their measurement uncertainties $u(\alpha)$ and $u(\beta)$ were determined using the Hildreth-Lu method for $\rho = 0.2$ [13, 14].

2.2 Risk Calculation

The global consumer risk R_C represents the probability where the measured value is within the acceptance interval, and the true value of an item of interest is outside the tolerance interval [5]. It is calculated as the sum of two double integrals, and holds $R_C = I_1 + I_2$, where:

$$I_1 = \int_{-\infty}^{T_L} \int_{A_L}^{A_U} g_0(\eta) h(\eta_m \mid \eta) \mathrm{d}\eta_m \mathrm{d}\eta, \quad (8)$$

$$I_1 = \int_{T_U}^{\infty} \int_{A_L}^{A_U} g_0(\eta) h(\eta_m \mid \eta) \mathrm{d}\eta_m \mathrm{d}\eta. \quad (9)$$

The global producer risk R_P represents the probability that the measured value is outside the acceptance interval, and that the true value is within the tolerance interval. It can also be expressed as the sum of two double integrals, and the following holds $R_p = I_3 + I_4$, where:

$$I_3 = \int_{-\infty}^{A_L} \int_{T_L}^{T_U} g_0(\eta) h(\eta_m \mid \eta) \mathrm{d}\eta_m \mathrm{d}\eta, \quad (10)$$

$$I_4 = \int_{A_U}^{\infty} \int_{T_L}^{T_U} g_0(\eta) h(\eta_m \mid \eta) \mathrm{d}\eta_m \mathrm{d}\eta. \quad (11)$$

For the prior g_0, a normal distribution with parameters y_0 and u_0 is assumed. Considering that the risk during calibration for the given values of the response variable y_r is calculated for the points of the moderate scale, this leads to role changes. The best estimates of y_0 in the risk assessment during calibration, for a given value of the response variable y_r, are calculated from the appropriate equation for the explanatory variable x_e:

$$y_0 \equiv x_{e_i} = \frac{y_{r_i} - \alpha}{\beta}, \; i = 1, 2, \ldots, n. \quad (12)$$

The response variable y_{r_i}, $i = 1, 2, \ldots, n$ takes on values in the interval of [–3.0279, 3.0224] µm.

The measurement uncertainty of the prior is given by Eq. (6). The measurement uncertainty u_m is the uncertainty of some future measurement process. This process is independent of the measurements from which the regression line from Eq. (7) was obtained. The expression for the likelihood function h contains the parameter u_m. In this work, it is assumed that $u_m = 0.5u_0$. The likelihood function is also modelled as a normal distribution.

The width of the tolerance interval is set so that it depends on the measurement uncertainty $u_0^{LRA}(x_i)$ of the points of the moderate scale and amounts to $\Delta T = 6\min(u_0^{LRA}(x_i))$, $i = 1, 2, \ldots, n$. This way, the linearized tolerance interval is derived from the measurement uncertainty u_0^{LRA}. Holds that $a_L = a_U = 3\min(u_0^{LRA}(x_i))$ for each point of moderate scale x_i, $i = 1, 2, \ldots, n$. The width of the acceptance interval ΔA when it holds that is $[A_L, A_U] \subset [T_L, T_U]$ amounts to $\Delta A = 0.8\Delta T$. For $[T_L, T_U] \subset [A_L, A_U]$, it holds that $\Delta A = 1.2\Delta T$. In both cases, the width of the guard band is equal to $w = 0.1\Delta T$. Detailed formulas for the calculation of the global risk for the producer and consumer, taking into account all the aforementioned parameters, can be found in [10]. These are omitted here for simplicity.

3 RESULTS AND DISCUSIONS

As well as in regression models, in risk assessment models for calibration the risk curves along the moderate scale are parabolas that are open upward, Fig. 3 [10]. The minimum is achieved for x_{min} = 0.3317 µm and is located at the point of intersection of the regression line from Eq. (7) and the line $y = x$. Since measurement uncertainty is always higher at the edges of the scale, the risk of calibrating is also higher at the edges. From Fig. 3, it can also be observed that the global risk for both the producer and the consumer is higher on the left side of the moderate scale. The global producer's risk values range from 0.05% to 15.1%, while the global consumer's risk values range from 0.2% to 5.3%.

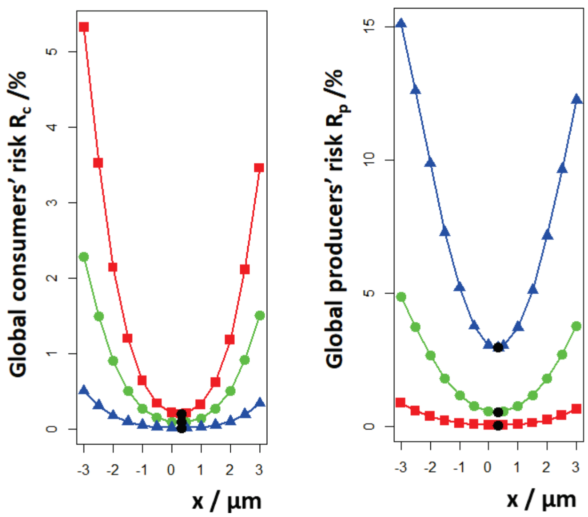

Figure 3 Risk curves along a moderate scale: —■— $[T_L, T_U] \subset [A_L, A_U]$, —●— $[T_L, T_U] = [A_L, A_U]$, —▲— $[T_L, T_U] \supset [A_L, A_U]$, ● Minimum point

Along the guard band axis, the global producer's risk increases, while the global consumer's risk decreases, as shown in Fig. 4.

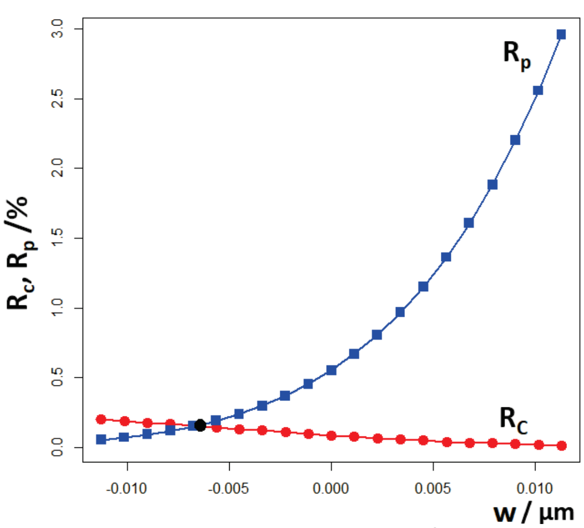

Figure 4 The risk curves along a guard band axis: —●— Global consumer's risk R_c, —■— Global producer's risk R_p, ● Intersection point

In Fig. 4, the values of global producer and consumer risk evaluated at the minimum point x_{min} are presented. Thus, these curves are commonly referred to as minimum curves. Negative values of the guard band width w indicate the situation where is $[T_L, T_U] \subset [A_L, A_U]$, while positive values correspond to the situation where is $[T_L, T_U] \supset [A_L, A_U]$. For $w = 0$, it holds that $[T_L, T_U] = [A_L, A_U]$. The risk curves shown in Fig. 4 intersect at $w \approx -0.0067$ µm, which corresponds to $\Delta A \approx 1.12\Delta T$. In this case, the global producer's and consumer's risk are equal, and both amount to $R_p = R_c \approx$ 0.15%.

Finally, the behaviours of the risk curves along the moderate scale and the guard band axis can be clearly discerned by observing the risk surfaces depicted in Fig. 5.

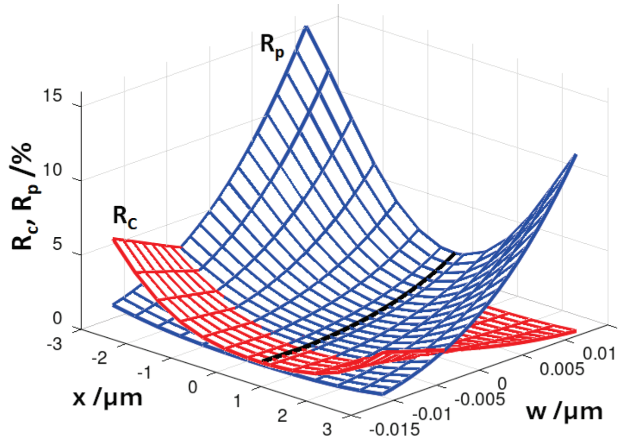

Figure 5 Risk surfaces: — Global consumer's risk R_c, — Global producer's risk R_p, — Curves of a minimum

The risk surfaces from Fig. 5 are presented on a discretized domain bounded by the intervals [–3, 3] µm on the moderate scale and by the interval [–0.011, 0.011] µm on the guard band axis. The highlighted lines on the risk surfaces in Fig. 5 correspond to the minimum curves presented in Fig. 4.

4 MODEL EVALUATION

The risk assessment model for calibration can be evaluated using confusion matrices by incorporating the conformance probability p_C in the calculations. The conformance probability indicates the degree of adherence to specified requirements [5]. When both the prior and likelihood functions follow a normal distribution, as noted in [5, 10], the conformance probability p_C for the values x_{e_i}, i = 1, 2, …, n is calculated using the equation:

$$p_{C_i} = \frac{1}{u_0^{LRA}\sqrt{2\pi}} \int_{T_{L_i}}^{T_{U_i}} \exp\left[-\frac{1}{2}\left(\frac{\eta - x_{e_i}}{u_0^{LRA}}\right)^2\right] d\eta. \quad (13)$$

The behaviour of the conformance probability along the guard band axis is described by straight lines. These lines are parallel to the guard band axis. The line of maximum values follows the equation p_C = 0.9972 and is achieved at the points (x_{min}, w), where $w \in$ [–0.011, 0.011] µm. Along the moderate scale axis, the conformance probability curves are parabolas opening downward, with maxima at the moderate scale point x_{min}, as shown in Fig. 6.

If the true value of the characteristic of an item of interest falls within the tolerance interval, and the measured value falls within the acceptance interval, this constitutes a valid acceptance of an item of interest, i.e. a true positive value (*TP*). Conversely, if the true value of an item of interest is outside the tolerance interval and at the same time the measured value is outside the acceptance interval, it is about valid rejection, i.e. a true negative value (*TN*). The global producer's risk R_P corresponds to the probability of false rejection (FR), while the global consumer's risk R_C represents the probability of false acceptance (FA). The classes *TP*, *TN*, R_C, and R_P represent the elements of the confusion matrix. Holds that $TP = p_C - R_p$, $TN = 1 - p_C - R_C$ [7, 15].

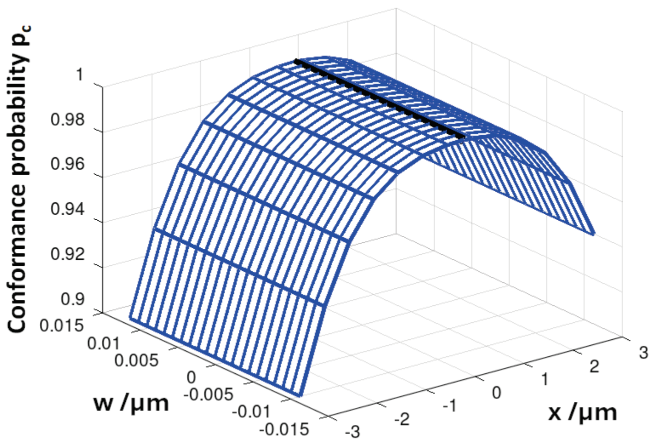

Figure 6 Conformance probability surface, — line of maximum values

Establishing a connection between conformance probability and classes of the confusion matrix allows the evaluation of models for risk assessment in calibration using confusion matrix-based metrics. The confusion matrix is defined based on the true value and the measured value, considering both the tolerance interval and the acceptance interval [7, 15]. The calibration of an inductive contact probe's risk assessment model was evaluated using standard metrics: accuracy, precision, recall, and F1 score, as illustrated in Fig. 7 [16].

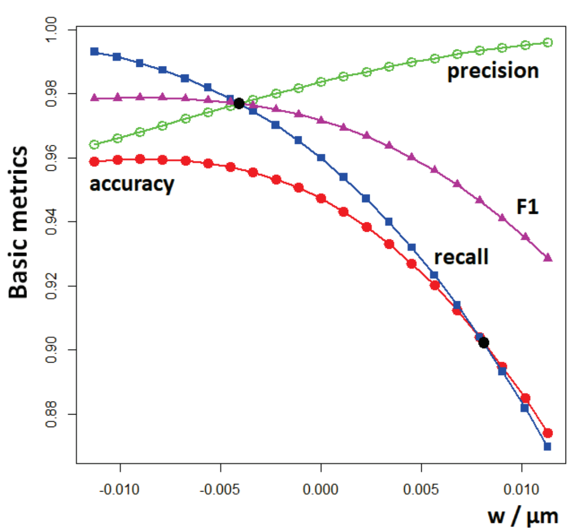

Figure 7 Basic metrics: —●— accuracy, —■— recall, —▲— F1, —○— precision

The metrics behaviours presented in Fig. 7 correspond to the case where $[T_L, T_U] \supset [A_L, A_U]$. This model is most considered in practice due to its consumer-favourable nature. In this scenario, the consumer's risk is minimized, while the producer's risk is maximized. Accuracy represents the ability of the model to classify *TP* and *TN* values concerning the total amount of data. This metric is not suitable for unbalanced data due to the prevalence of the *TP* class [17]. Recall is defined as the probability that true positive values fall within the tolerance interval. Due to its dependence on the global producer's risk, recall decreases along the guard band axis [15]. For $w \approx 0.008$ μm it holds that *accuracy* = *recall* ≈ 0.9 and $\Delta A \approx 0.85\Delta T$. Precision measures a model's ability to identify true positive values that fall within the acceptance interval. Since precision is influenced by global consumer's risk, it diminishes along the guard band axis [15]. To avoid the trade-offs between precision and recall, the F1 score metric is considered. *F*1 score is the harmonic mean of precision and recall. It also measures model accuracy but is more suitable for imbalanced data [17]. *F*1 score shadowing standard accuracy, attaining higher values, as shown in Fig. 7. The precision, recall and F1 score intersect each other when it holds that $R_C = R_p$. This occurs when the width of the guard band is equal to $w \approx -0.004$ μm. Then holds $R_C = R_p \approx 2.17\%$ and $\Delta A \approx 1.07\Delta T$. Under these conditions, the metric values are *recall* = *precision* = *F*1 = 0.9769. The maximum values of accuracy metrics and *F*1 score metrics are achieved at the moderate scale point x_{min} where is *accuracy* = 0.9961 and *F*1 = 0.9980. Fig. 8 presents the surface of the *F*1 score metrics, highlighting the curve of maximum values.

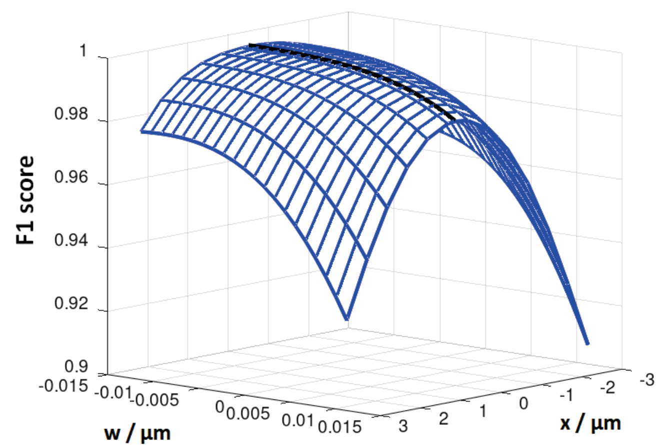

Figure 8 F1 score surface

All metrics on the domain exhibit high values, with probabilities ranging from 0.83 to 1. Additionally, the values for conformance probability are also high, ranging from 0.90 to 0.9972.

The outlined procedure for risk assessment in calibration identifies areas of highest and lowest risk, enabling a quantitative evaluation of the calibration process. It can be concluded that the greatest risk in calibrating the inductive contact probe occurred for the measurements obtained on the left side of the moderate scale in the model where $[T_L, T_U] \supset [A_L, A_U]$.

5 CONCLUSIONS

This study has described a method for assessing the risk of making wrong decisions during calibration. So far, such a risk assessment procedure for calibration in metrology has not yet been applied. The significance and practical effects of this risk assessment method for calibration should be viewed in the context of ensuring accurate and reliable measurements. A brief overview of risk assessment for the trivial, linearized model is provided, utilized alongside measurement uncertainty derived from extensive data on measurement performance. Emphasis is placed on the description of the linearized model where the measurement uncertainty is calculated from the available data about the calibration curve. It is demonstrated that this method can identify those areas of the domain where the risks incurred during the measurement are the highest. The evaluation of the model was carried out according to the confusion matrix-based metrics. The quality of the calibration procedure is indicated by the high values of standard metrics. Beyond metrology, this calibration risk assessment model could be applied in chemistry, medicine, economics, and other fields. For future work, it remains to describe a non-linearized risk assessment model for calibration.

6 REFERENCES

[1] Separovic, L., de Godoy Bertanha, M. L., Saviano, A. M., & Lourenço, F. R. (2020). Conformity decisions based on measurement uncertainty—a case study applied to agar diffusion microbiological assay. *Journal of Pharmaceutical Innovation*, *15*, 110-115. https://doi.org/10.1007/s12247-019-09374-8

[2] Runje, B., Horvatic Novak, A., Razumic, A., Piljek, P., Strbac, B., & Orosnjak, M. (2019, October). Evaluation of consumer and producer risk in conformity assessment decisions. In *Proceedings of the 30th DAAAM international symposium* (pp. 0054-0058). https://doi.org/10.2507/30th.daaam.proceedings.007

[3] Božić, D., Runje, B., & Razumić, A. The Cost of Wrong decisions. In *The 19th International Conference" Laboratory Competence-Brijuni 2024"*.

[4] Hibbert, D. B., Korte, E. H., & Örnemark, U. (2021). Metrological and quality concepts in analytical chemistry (IUPAC Recommendations 2021). *Pure and Applied Chemistry*, *93*(9), 997-1048. https://doi.org/10.1515/pac-2019-0819

[5] BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML. Evaluation of measurement data — The role of measurement uncertainty in conformity assessment. Joint Committee for Guides in Metrology, JCGM 106:2012. https://doi.org/10.59161/jcgm106-2012

[6] Lira, I. (1999). A Bayesian approach to the consumer's and producer's risks in measurement. *Metrologia*, *36*(5), 397. https://doi.org/10.1088/0026-1394/36/5/1

[7] Božić, D., & Runje, B. (2022, October). Selection of an Appropriate Prior Distribution in Risk Assessment. In *Proceedings of the 33rd International DAAAM Virtual Symposium "Intelligent Manufacturing & Automation", Vienna, Austria* (pp. 26-27). https://doi.org/10.2507/33rd.daaam.proceedings.066

[8] Toczek, W., & Smulko, J. (2021). Risk Analysis by a Probabilistic Model of the Measurement Process. *Sensors*, *21*(6), 2053. https://doi.org/10.3390/s21062053

[9] Koucha, Y., Forbes, A., & Yang, Q. (2021). A Bayesian conformity and risk assessment adapted to a form error model. *Measurement: Sensors*, *18*, 100330. https://doi.org/10.1016/j.measen.2021.100330

[10] Božić, D., Runje, B., & Razumić, A. (2024). Risk Assessment for Linear Regression Models in Metrology. *Applied Sciences*, *14*(6), 2605. https://doi.org/10.3390/app14062605

[11] Heckert, N. A., Filliben, J. J., Croarkin, C. M., Hembree, B., Guthrie, W. F., Tobias, P., & Prinz, J. (2002). Handbook 151: Nist/sematech e-handbook of statistical methods. Retrieved from http://www.itl.nist.gov/div898/handbook/mpc/mpc.htm

[12] Bednjanec, F. (2016). Umjeravanje uređaja za mjerenje kružnosti (Diplomski rad). Zagreb: Sveučilište u Zagrebu, Fakultet strojarstva i brodogradnje. Retrived from https://urn.nsk.hr/urn:nbn:hr:235:701539 (in Croatian)

[13] Subhi, K. T., & Al Azkiya, A. (2022). Comparison of Cochrane-Orcutt and Hildreth-Lu methods to overcome autocorrelation in time series regression (case study of Gorontalo province HDI 2010-2021). *Parameter: Journal of Statistics*, *2*(2), 30-36. https://doi.org/10.22487/27765660.2022.v2.i2.15913

[14] Young, D. S. (2018). *Handbook of regression methods.* Chapman and Hall/CRC.

[15] Božić, D., Runje, B., Lisjak, D., & Kolar, D. (2023). Metrics related to confusion matrix as tools for conformity assessment decisions. *Applied Sciences*, *13*(14), 8187. https://doi.org/10.3390/app13148187

[16] Tharwat, A. (2021). Classification assessment methods. *Applied computing and informatics*, *17*(1), 168-192. Retrieved from https://www.emerald.com/insight/publication/issn/2634-1964/vol/17/iss/1

[17] Jeni, L. A., Cohn, J. F., & De La Torre, F. (2013, September). Facing imbalanced data--recommendations for the use of performance metrics. In *2013 Humaine association conference on affective computing and intelligent interaction* (pp. 245-251). IEEE. https://doi.org/10.1109/ACII.2013.47

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Ball and Plate Mechanism Actuated with Pneumatic Artificial Muscles

Juraj Benić*, Andreas Šantek, Željko Šitum

Abstract: A novel ball-and-plate mechanism actuated with pneumatic artificial muscles is presented in this paper. The pneumatic muscles are arranged in two antagonistic configuration pairs to generate torque around two axes of plate rotation. The ball-and-plate system is classified as an under-actuated, high-order nonlinear system, with additional nonlinearities introduced by the air compressibility of the pneumatic muscles. A nonlinear mathematical model of the ball-and-plate system has been derived, in which the proposed system is modelled as two ball-and-beam systems, each representing one direction of the ball's movement. Along with the nonlinear equations of motion, a simplified dynamical model of the pneumatic muscles and the proportional valve is included. The linearized model is developed and represented in a state-space form, which is used for LQR controller synthesis. The proposed controller is tested through numerical simulations and experimentally validated on the developed ball-and-plate mechanism setup.

Keywords: ball and plate; LQR; mathematical modeling; pneumatics muscles

1 INTRODUCTION

The ball-and-plate system is an extension of the two-degrees-of-freedom (DOF) ball-and-beam system [1] to a four-DOF problem. This system is considered a benchmark problem in control theory due to its nonlinear, multivariable, under-actuated, and unstable open-loop dynamics. The control challenges associated with the ball-and-plate system are typically divided into two categories: point stabilization [2] and trajectory tracking [3]. Various control methods have been applied to address these challenges, including PID controllers [4], LQR regulators [5], sliding mode controllers [6], model reference adaptive controllers [7], fuzzy controllers [8], neural networks and genetic algorithms [9], and, more recently, linear matrix inequalities [10].

From a pneumatic perspective, the ball-and-beam system with two pneumatic cylinders as actuators and a fuzzy P(I)D regulator was investigated in [11]. Similarly, in [12], the pneumatic cylinders were replaced with pneumatic artificial muscles (PAMs), and an LQR regulator was used to stabilize the system. In [13], researchers extended this approach by using two pneumatic cylinders to actuate a ball-and-plate mechanism. However, a review of the literature indicates that PAMs have not been used to stabilize a ball-and-plate mechanism.

PAMs are highly nonlinear pneumatic actuators due to their construction and the compressibility of air within them [14]. Their lightweight construction, high power-to-weight ratio, and ability to operate in explosive or hazardous environments make them ideal for medical and industrial applications. Over the years, many types of PAMs have been developed, including McKibben, Yarlott, Kukolj, Festo PAMs, and others. In this paper, Festo PAMs are used to actuate the ball-and-plate system, introducing additional nonlinearity to an already complex system.

This study addresses both the stabilization and trajectory tracking problems of a ball-and-plate mechanism actuated by four PAMs. It builds on our previous work described in [12]. Two antagonistic groups of pneumatic muscles are used to generate torque and achieve rotation about the plate's horizontal axis. An LQR regulator is employed to stabilize this highly nonlinear system. The regulator's performance is evaluated through two test scenarios: stabilizing the ball at the plate's center and having the ball follow a circular trajectory.

The remainder of this paper is organized as follows: Section 2 provides a detailed description of the experimental setup, while Section 3 outlines the mathematical modeling procedure for the proposed system. Section 4 presents experimental and simulation results, while conclusions and directions for future work are discussed in Section 5.

2 EXPERIMENTAL SETUP

The proposed ball-and-plate system, shown in Fig. 1, was developed in the Automation and Robotics Laboratory at the Faculty of Mechanical Engineering and Naval Architecture. The experimental setup serves both as a platform for research in pneumatic systems control and as a training tool for students.

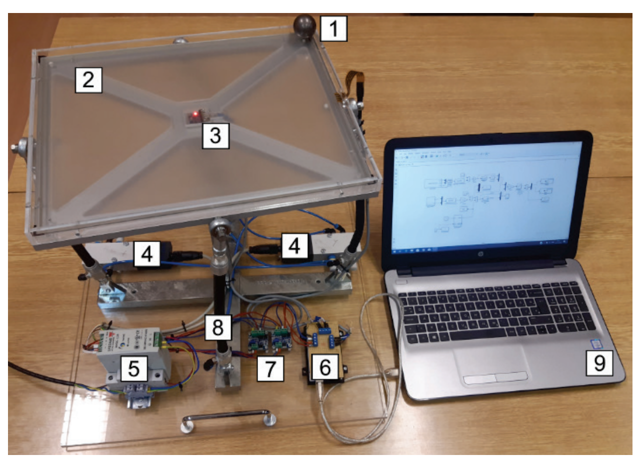

Figure 1 Ball and plate system actuated with PAMs

The experimental setup, shown in Fig. 1, consists of a steel ball (1) placed on a resistive four-wire analog 17-inch touchscreen (2). The position of the ball is detected by measuring the voltage drop (ranging from 0 to 5 V) across the X and Y axes. These measurements are processed by an Arduino Mega 2560 microcontroller (6). A key limitation of the resistive touchscreen is its inability to simultaneously measure both coordinates. This issue is resolved by measuring each position separately with a 1-microsecond delay, allowing sufficient time for voltage stabilization across the second axis. The touchscreen is mounted on a transparent plexiglass sheet, which is secured to a CNC-milled aluminum frame.

Angular velocity is measured using the widely utilized MPU 6050 gyroscope (3), which is also integrated into the aluminum frame. The MPU 6050 combines a three-axis gyroscope and a three-axis accelerometer in a single unit, offering four programmable angular velocity ranges (measured in degrees per second) and a built-in digital programmable low-pass filter. The gyroscope communicates with the microcontroller via the I2C protocol.

Two pairs of pneumatic artificial muscles (PAMs) (8) (Festo, type DMSP-10-200N-RM-CM) are arranged antagonistically to actuate a spherical joint. The torque required for plate actuation is achieved by creating a pressure differential between the pairs of PAMs, which causes the plate to rotate around the X and Y axes. This pressure differential is regulated by two proportional 5/3 control valves (4) (Festo, type MPYE-5 1/8 HF-010B), connected to a 24 VDC power supply (5).

To control the spool movement in the valves, an analog control signal ranging from 0 to 10 V is required. The flow rate and thus the pressure differential in the PAMs is adjusted by the spool's movement. The Arduino microcontroller generates a PWM signal in the range of 0 to 5 VDC. This PWM signal is converted to an analog signal (0 to 10 VDC) using two PWM-to-voltage converters (7), each controlling one proportional valve. By default, the Arduino's PWM output is set to 2.5 VDC, which, after conversion, provides 5 VDC to the valves, positioning the spools in their neutral state and maintaining approximately equal pressures in the muscles.

The controller is implemented using the MATLAB Simulink software installed on a PC (9). The control process utilizes custom-built blocks for the touchscreen, an additional library for the MPU 6050 gyroscope, and the Simulink Support Package for Arduino.

3 MATHEMATICAL MODELING

To achieve successful control of the ball-and-plate system, it is essential to derive a nonlinear mathematical model of the system. The following assumptions are made to simplify the analysis:

- the ball is an ideal sphere with a constant radius,
- the ball remains in continuous contact with the plate,
- there is no slipping between the ball and the plate,
- friction is negligible,
- the height of the plate is negligible.

The nonlinear dynamic model of the system is derived using the Lagrange method, where the Lagrange equation is expressed as:

$$L = K - P, \tag{1}$$

where K and P represent the total kinetic and potential energy of the system, respectively. The derivative of the Lagrangian is given by:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = T_i, \tag{2}$$

where q_i represents the generalized coordinates, and T_i is the moment around the corresponding generalized coordinate. Four generalized coordinates are defined as follows: $q_1 = x$ and $q_2 = y$ (representing the ball's position on the plate), and $q_3 = \theta_1$ and $q_4 = \theta_2$ (representing the plate angles around the X and Y axes). A schematic representation of the proposed system and the generalized coordinates is provided in Fig. 2.

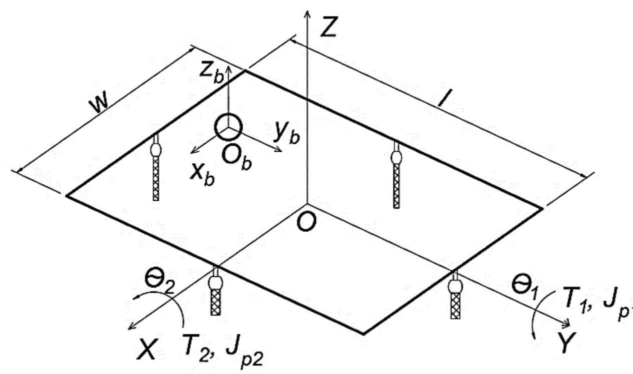

Figure 2 Schematic representation of ball on plate setup

The mathematical model of the experimental setup can be further simplified by representing the ball-and-plate system as two ball-and-beam systems. The first system moves the ball in the Y-direction, while the second moves it in the X-direction. The proposed simplified model of the ball-and-plate system is shown in Fig. 3, where the ball moves in the local OX_iY_i frame, with i indicating the number of the ball-and-beam system.

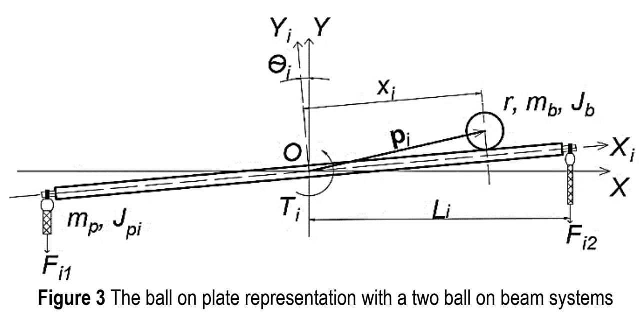

Figure 3 The ball on plate representation with a two ball on beam systems

The kinetic and potential energy of the proposed simplified model of the beam can be expressed as follows:

$$K_{pi} = \frac{1}{2} J_{pi} \dot{\theta}_i^2, \quad P_{pi} = 0, \tag{3}$$

where K_{pi} and P_{pi} represent the kinetic and potential energy of the plate, modeled as two beams. $\dot{\theta}_i$ is the angular velocity of the plate, and J_{pi} is the moment of inertia of the beam around the center of rotation, defined as:

$$J_{pi} = m_p \frac{l_i^2}{12}, \tag{4}$$

where m_p is plate mass and l_i is the length or width of the plate, depending on the X or Y axis as shown in Fig. 2. From Eq. (3) and Eq. (4), the total kinetic and potential energy of the plate can be defined as:

$$\begin{aligned} K_p &= \frac{1}{24} m_p \left(l^2 \dot{\theta}_2^2 + w^2 \dot{\theta}_1^2 \right), \\ P_p &= 0, \end{aligned} \tag{5}$$

where l and w are the length and width of the plate, respectively. The potential energy of the plate is considered zero due to the placement of the $OXYZ$ coordinate system at the center of gravity of the plate.

The potential energy of the ball, as shown in Fig. 3, can be expressed as follows:

$$P_{bi} = m_b \mathrm{g} \left(x_i \sin(\theta_i) + r \cos(\theta_i) \right), \tag{6}$$

where m_b and r are the mass and radius of the ball, respectively, g s the gravitational constant, θ_i is the plate angle, and x_i is the position of the plate in OX_iY_i frames. From Eq. (7), the total potential energy of the ball is derived as:

$$P_b = m_b \mathrm{g} \left[x \sin(\theta_1) + y \sin(\theta_2) + r \left(\cos(\theta_1) + \cos(\theta_2) \right) \right], \tag{7}$$

where x and y are the positions of the ball on the plate.

The kinetic energy of the ball consists of both translational and rotational energy and is expressed as:

$$K_{bi} = \frac{1}{2} m_b v_i^2 + \frac{1}{2} J_b \omega_i^2, \tag{8}$$

where $J_b = 2m_b r^2/5$ is the moment of inertia of a solid sphere, v_i is the translational velocity of the ball, and ω_i is the peripheral speed of the ball, defined as:

$$\omega_i = \frac{\dot{x}_i}{r}. \tag{9}$$

From Eq. (8) and Eq. (9), the kinetic energy of the ball is expressed as:

$$K_{bi} = \frac{1}{2} m_b v_i^2 + \frac{1}{2} \frac{J_b}{r^2} \dot{x}_i^2. \tag{10}$$

The translational velocity of the ball is derived from the position vector $\boldsymbol{p}_i$ which connects the origin of the OXY frame to the center of the ball. From Fig. 3, using the rotation matrix around the Z-axis, the vector $\boldsymbol{p}_i$ can be written as:

$$\boldsymbol{p}_i = \begin{bmatrix} x_i \cos(\theta_i) - r \sin(\theta_i) \\ x_i \sin(\theta_i) + r \cos(\theta_i) \end{bmatrix}, \tag{11}$$

and its derivative can be written as:

$$\dot{\boldsymbol{p}}_i = v_i = \begin{bmatrix} \dot{x}_i \cos(\theta_i) - x_i \dot{\theta}_i \sin(\theta_i) - r \dot{\theta}_i \cos(\theta_i) \\ \dot{x}_i \sin(\theta_i) + x_i \dot{\theta}_i \cos(\theta_i) - r \dot{\theta}_i \sin(\theta_i) \end{bmatrix}. \tag{12}$$

From Eq. (12) v_i^2 is obtained as:

$$v_i^2 = \dot{x}_i^2 - 2r \dot{x}_i \dot{\theta}_i + r^2 \dot{\theta}_i^2 + x^2 \dot{\theta}^2. \tag{13}$$

Inserting Eq. (13) into Eq. (10) yields:

$$K_{bi} = \frac{1}{2} m_b \left(\dot{x}_i^2 - 2r \dot{x}_i \dot{\theta}_i + r^2 \dot{\theta}_i^2 + x^2 \dot{\theta}^2 \right) + \frac{1}{2} \frac{J_b}{r^2} \dot{x}_i^2. \tag{14}$$

From Eq. (14) kinetic energy of the ball in the global coordinate system from Fig. 2, is expressed as:

$$\begin{aligned} K_b &= \frac{1}{2} \left(m_b + \frac{J_b}{r^2} \right) (\dot{x}^2 + \dot{y}^2) + \\ &+ \frac{1}{2} m_b \left(x^2 \dot{\theta}_1^2 - 2r x \dot{\theta}_1 + r^2 \dot{\theta}_1^2 + y^2 \dot{\theta}_2^2 - 2r y \dot{\theta}_2 + r^2 \dot{\theta}_2^2 \right). \end{aligned} \tag{15}$$

From Eq. (5), Eq. (7), and Eq. (15), the total kinetic and potential energy is defined as:

$$\begin{aligned} K &= K_p + K_b, \\ P &= P_p + P_b. \end{aligned} \tag{16}$$

From Eq. (2) to Eq. (16), and with the previously defined generalized coordinates, the nonlinear mathematical model of the ball-and-plate system is obtained as follows:

$$\begin{aligned} &\left(m_b + \frac{J_b}{r^2} \right) \ddot{q}_1 - m_b r \ddot{q}_3 - m_b q_1 \dot{q}_3^2 + \mathrm{g} m_b \sin(q_3) = 0, \\ &\left(m_b + \frac{J_b}{r^2} \right) \ddot{q}_2 - m_b r \ddot{q}_4 - m_b q_2 \dot{q}_4^2 + \mathrm{g} m_b \sin(q_4) = 0, \\ &\left(m_p \frac{w^2}{12} + m_b r^2 + m_b q_1^2 \right) \ddot{q}_3 + m_b (2 q_1 \dot{q}_1 \dot{q}_3 - r \ddot{q}_1) + \\ &+ m_b \mathrm{g} \left(q_1 \cos(q_3) - r \sin(q_3) \right) = T_1, \\ &\left(m_p \frac{w^2}{12} + m_b r^2 + m_b q_2^2 \right) \ddot{q}_4 + m_b (2 q_2 \dot{q}_2 \dot{q}_4 - r \ddot{q}_2) + \\ &+ m_b \mathrm{g} \left(q_2 \cos(q_4) - r \sin(q_4) \right) = T_2. \end{aligned} \tag{17}$$

The applied torque T_i (Fig. 3) for rotating the beam can be calculated from the muscle contraction forces F_{i1} and F_{i2} as derived in [12, 15, 16], using the following expression:

$$T_i = K_i \Delta p_i, \tag{18}$$

where Δp_i is the pressure difference inside the PAMs, and K_i is defined as:

$$K_i = \frac{\pi}{2} L_i D_0^2 \left[3\tan^2(\alpha_0)(1-\epsilon_0)^2 - \sin^2(\alpha_0) \right], \tag{19}$$

where L_i is the distance from the center of rotation, D_0 and ϵ_0 are the nominal diameter and initial contraction ratio of the PAMs, respectively, and α_0 is the initial angle of the braided shell between the thread and the long axis of the PAM.

The pressure dynamics in the PAMs can be represented by the first-order lag term as:

$$\tau_v \Delta \dot{p}_i + \Delta p_i = K_v u_i, \tag{20}$$

where K_v and τ_v are the valve gain and time constant, respectively, and u_i is the input voltage to the pneumatic proportional valve.

3.1 Linearized Mathematical Model

The linearized equations of motion around the equilibrium state will be derived from Eq. (17). The assumptions on which the linear model is based are:

- small angles of rotation: $\sin(\Delta q_i) \cong \Delta q_i$ and $\cos(\Delta q_i) \cong 1$
- small angular velocity: $\dot{q}_3 \cong \dot{q}_4 \cong 0$
- small ball displacements: $q_1^2 \cong q_2^2 \cong 0$
- small ball translational velocity: $\dot{q}_1^2 \cong \dot{q}_2^2 \cong 0$.

Applying the proposed assumptions, the effects of the Coriolis and centrifugal forces can be neglected from the equations of motion, yielding a dynamical model as:

$$\begin{aligned}
&\left(m_b + \frac{J_b}{r^2}\right)\ddot{q}_1 - m_b r \ddot{q}_3 + \mathrm{g} m_b q_3 = 0, \\
&\left(m_b + \frac{J_b}{r^2}\right)\ddot{q}_2 - m_b r \ddot{q}_4 + \mathrm{g} m_b q_4 = 0, \\
&\left(m_p \frac{w^2}{12} + m_b r^2\right)\ddot{q}_3 - m_b r \ddot{q}_4 + m_b \mathrm{g}(q_1 - r q_3) = T_1, \\
&\left(m_p \frac{w^2}{12} + m_b r^2\right)\ddot{q}_4 - m_b r \ddot{q}_2 + m_b \mathrm{g}(q_2 - r q_4) = T_2.
\end{aligned} \tag{21}$$

By comparing the masses of the ball and the plate, it can be concluded that the ball mass is much smaller than the plate mass. If $m_b << m_p$, then the influence of the ball dynamics on the plate dynamics in Eq. (21) can be neglected. Using Eq. (18) and Eq. (20), the simplified linearized mathematical model is given as:

$$\begin{aligned}
\ddot{q}_1 &= -\frac{5}{7}\mathrm{g} p_3 + \frac{60 r K_1}{7 m_p w^2}\Delta p_1, \\
\ddot{q}_2 &= -\frac{5}{7}\mathrm{g} p_4 + \frac{60 r K_2}{7 m_p l^2}\Delta p_2, \\
\ddot{q}_3 &= \frac{12 K_1}{m_p w^2}\Delta p_1, \\
\ddot{q}_4 &= \frac{12 K_2}{m_p l^2}\Delta p_2, \\
\Delta \dot{p}_1 &= -\frac{1}{\tau_v}\Delta p_1 + \frac{K_v}{\tau_v} u_1, \\
\Delta \dot{p}_2 &= -\frac{1}{\tau_v}\Delta p_2 + \frac{K_v}{\tau_v} u_2.
\end{aligned} \tag{22}$$

From Eq. (22) the linearized state-space model is derived as:

$$\begin{aligned}
\boldsymbol{x} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}, \\
\boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u},
\end{aligned} \tag{23}$$

where the state space variables are defined as

$$\boldsymbol{x} = \left[q_1, \dot{q}_1, q_2, \dot{q}_2, q_3, \dot{q}_3, q_4, \dot{q}_4, \Delta p_1, \Delta p_2 \right]^{\mathrm{T}}.$$

3.2 Controller Design

In this paper, the Linear Quadratic Regulator (LQR) will be used to stabilize a highly nonlinear system. The proposed controller will be designed to stabilize the system at the equilibrium point and will also be tested for tracking a circular trajectory. The LQR method is a state-feedback controller that determines the optimal gains for the state variables based on two matrices, $\boldsymbol{Q}$ and $\boldsymbol{R}$. The matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ are selected iteratively, with a good starting point for the parameters chosen as:

$$\begin{aligned}
Q_{ii} &= \frac{1}{\max(x_i)^2}, \\
r &= \frac{1}{\max(u)^2},
\end{aligned} \tag{24}$$

where x_i is the maximum deviation of the state-space variable and u is the maximal controller output.

The infinite-horizon, continuous-time LQR controller is based on minimizing the following performance criterion:

$$J = \int_0^\infty (\boldsymbol{x}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{x} + \boldsymbol{u}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{u})\mathrm{d}t, \tag{25}$$

where the feedback control law that minimizes the value of the cost is $\boldsymbol{u} = \boldsymbol{K}\boldsymbol{x}$.

4 SIMULATION AND EXPERIMENTAL RESULTS

Numerical simulations are based on the state-space model from Eq. (23) and the LQR controller. The parameters used for the numerical simulation are shown in Tab. 1. Simulations are performed in Matlab using the ODE routine.

Table 1 Parameters of the ball and plate system

Symbol	Parameter	Value
m_b	mass of the ball	0.067 kg
m_p	mass of the plate	2.7 kg
r	radius of the ball	0.013 m
w	width of the plate	0.360 m
l	length of the plate	0.290 m
g	acceleration due to gravity	9.81 m/s2
D_0	nominal diameter of the muscle	0.01 m
α_0	initial angle of the braided shell	22 deg
ϵ_0	initial contraction ratio of the muscle	0.1
K_v	gain of the proportional valve	1.1105 Pa/V
τ_v	time constant of the proportional valve	0.05 s

Fig. 4 shows the simulation results for the simplified and linearized dynamical model from Eq. (23). The results demonstrate good performance in stabilizing the ball at the equilibrium point, as well as a strong response to external disturbances.

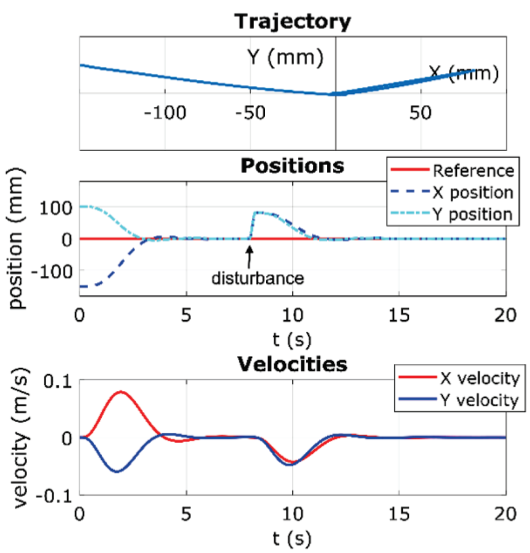

Figure 4 Simulation results - equilibrium point with disturbances

Experimental results for stabilizing the ball at the equilibrium point and for tracking the desired trajectory are shown in Fig. 5 and Fig. 6. The first diagram shows the ball trajectory in the *XY* plane. The second diagram displays the *X*, *Y*, and reference ball positions, while the third diagram presents the ball velocities. In both cases, the LQR controller demonstrated strong performance. High-amplitude external disturbances, during the ball stabilization at the equilibrium point, were effectively rejected by the LQR controller within approximately 5 seconds, with minimal deviation from the center of the plate. The experimental results also show that the LQR controller can track the circular trajectory of the highly nonlinear system actuated by pneumatic muscles, with only a small deviation from the reference trajectory.

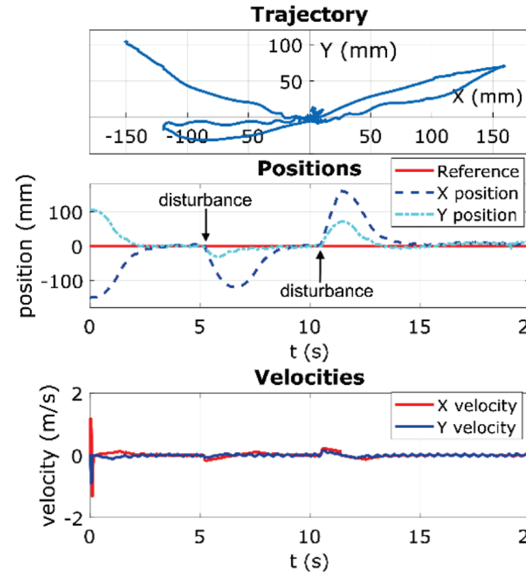

Figure 5 Experimental results - equilibrium point with disturbances

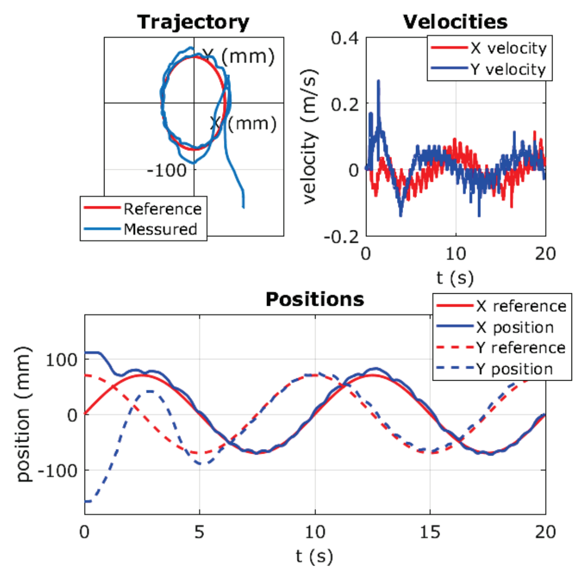

Figure 6 Experimental results - trajectory tracking

5 CONCLUSION

In this paper, a nonlinear mathematical model of the ball and plate mechanism actuated by pneumatic muscles is derived using the Lagrangian method. Nonlinearities due to air compressibility, pneumatic muscles, and the proportional valve were simplified and represented using a first-order lag term. The linearized model was derived around an equilibrium point with certain assumptions and approximations. The LQR controller was derived from the linearized model, and simulation results demonstrated good performance in stabilizing the ball at the equilibrium point and in trajectory tracking.

Experimental results showed minimal deviation from the simulation results for the LQR controller and confirmed that the simplifications and assumptions made during the linearization process had a minimal impact on the system dynamics. However, while LQR control proved effective, it may not be optimal for handling large nonlinearities. More advanced adaptive control strategies, such as Model Predictive Control (MPC) or Reinforcement Learning (RL), could be explored in future work to improve performance.

Furthermore, while the study simplified the pneumatic artificial muscles (PAMs) using a first-order lag model, PAMs inherently exhibit additional nonlinearities such as hysteresis and air compressibility effects. A more detailed modeling approach could enhance accuracy and provide a deeper understanding of the system dynamics. Additionally, the experimental validation focused on short-term performance, whereas a long-term analysis, considering environmental variations such as temperature and air pressure fluctuations, could offer insights into the system's robustness.

The comparison between experiment and simulations was limited to a single parameter setting, which may not capture the full range of system behavior. A more comprehensive Design of Experiments (DoE) approach could help explore model sensitivities and improve generalizability.

6 REFERENCES

[1] Rose, C. G., Bucki, N. & O'Malley, M. K. (2017). A ball and beam module for a haptic paddle education platform. *American Society of Mechanical Engineers, 3*. https://doi.org/10.1115/DSCC2017-5027

[2] Galvan-Colmenares, S., Moreno-Armendariz, M. A., de Jesus Rubio, J., Ortíz-Rodriguez, F., Yu, W. & Aguilar-Ibanez, C. F. (2014). Dual PD control regulation with nonlinear compensation for a ball and plate system. *Mathematical Problems in Engineering, 2014*, 1-10. https://doi.org/10.1155/2014/894209

[3] Liu, H. & Liang, Y. (2010). Trajectory tracking sliding mode control of ball and plate system. In *The 2nd IEEE International Asia Conference on Informatics in Control, Automation and Robotics (CAR 2010)*, 1-5.

[4] Aphiratsakun, N. & Otaryan, N. (2016). Ball on the plate model based on PID tuning methods. In *The 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON2016)*, 1-4. https://doi.org/10.1109/ECTICon.2016.7561324

[5] Dusek, F., Honc, D. & Sharma, K. R. (2017). Modelling of ball and plate system based on first principle model and optimal control. In *The 21st IEEE International Conference on Process Control (PC2017)*, 1-5. https://doi.org/10.1109/PC.2017.7976216

[6] Debono, D. & Bugeja, M. (2015). Application of sliding mode control to the ball and plate problem. In T*he 12th International Conference on Informatics in Control, Automation and Robotics (ICINCO2015), 01*, 412-419. https://doi.org/10.5220/0005569804120419

[7] Mani, G., Sivaraman, N. & Kannan, R. (2018). Visual servoing based model reference adaptive control with Lyapunov rule for a ball on plate balancing system. In *IEEE International Conference on Intelligent and Advanced System (ICIAS2018)*, 1-6. https://doi.org/10.1109/ICIAS.2018.8540635

[8] Fan, X., Zhang, N. & Teng, S. (2004). Trajectory planning and tracking of ball and plate system using hierarchical fuzzy control scheme. *Fuzzy Sets and Systems, 144*(2), 297-312. https://doi.org/10.1016/j.fss.2003.11.008

[9] Dong, X., Zhang, Z. & Chen, C. (2009). Applying genetic algorithm to on-line updated PID neural network controllers for ball and plate system. In *Fourth IEEE International Conference on Innovative Computing, Information and Control (ICICIC2009)*, 1-4. https://doi.org/10.1109/ICICIC.2009.113

[10] Mochizuki, S. & Ichihara, H. (2013). I-PD controller design based on generalized KYP lemma for ball and plate system. In *IEEE European Control Conference (ECC2013)*, 1-6. https://doi.org/10.23919/ECC.2013.6669269

[11] Azman, M. A., Faudzi, A. A. M., Mustafa, N. D., Osman, K. & Natarajan, E. (2014). Integrating servopneumatic actuator with ball beam system based on intelligent position control. *Jurnal Teknologi, 69*(3), 47-53. https://doi.org/10.11113/jt.v69.3146

[12] Šitum, Ž. & Trslić, P. (2018). Ball and beam balancing mechanism actuated with pneumatic artificial muscles. *Journal of Mechanisms and Robotics, 10*(5), 1-8. https://doi.org/10.1115/1.4040103

[13] Zhao, W. (2013). A study of the ball-and-plate system driven by pneumatic direct cylinders. *Applied Mechanics and Materials, 310*, 294-303. https://doi.org/10.4028/www.scientific.net/AMM.310.294

[14] Scaff, W., Horikawa, O. & de Sales Guerra Tsuzuki, M. (2018). Pneumatic artificial muscle optimal control with simulated annealing. *IFAC-PapersOnLine, 51*(27), 333-338. https://doi.org/10.1016/j.ifacol.2018.08.141

[15] Tondu, B. & Lopez, P. (2000). Modeling and control of McKibben artificial muscle robot actuators. *IEEE Control Systems Magazine, 20*(2), 15-38. https://doi.org/10.1109/37.846122

[16] Schroder, J., Erol, D., Kawamura, K. & Dillman, R. (2003). Dynamic pneumatic actuator model for a model-based torque controller. In *Proceedings IEEE International Symposium on Computational Intelligence in Robotics and Automation*, 1-6. https://doi.org/10.1109/CIRA.2003.1243644

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Real-Time Monitoring of the CO_2 Footprint of Production for SMEs

Henning Strauß*, Julian Sasse

Abstract: The core of the research work is the development and implementation of a real-time product carbon footprint with a focus on applicability for small and medium-sized enterprises. In addition to the life cycle analysis, a central element is the implementation of a machine carbon footprint for a 5-axis universal machining center that records and visualizes resource consumption in real time. With the help of a wide range of sensors, consumption such as energy, compressed air and cooling lubricants are dynamically measured as well as material consumption. The measurement data is then processed, stored and visualized with the help of open-source low-code platforms. This real-time data forms the basis for the precise determination of the production-specific CO_2 footprint. The results of the Product Carbon Footprint show that the greatest savings potential lies in the choice of sustainable raw materials (a reduction of 38%) and the use of renewable energies (a reduction of 19%). The approach offers a high level of transparency and supports companies in optimizing their processes as well as meeting future regulatory requirements.

Keywords: CO_2 Footprint; IoT; Machine Data Acquisition; Open Source Software (OSS); Process Data; Production

1 INTRODUCTION

In Germany, the manufacturing industry is responsible for 23% of CO_2 equivalent emissions [1]. In recent years, however, increased efforts to reduce emissions have been observed [2]. The background to this development is, for example, the increased efficiency of production processes, especially with regard to the resources used. In addition, policies such as the CSRD Directive and the European Union's Green Deal help to further reduce emissions. Companies are forced to record, store and visualize CO_2 data, i.e. document it, in order to identify further potential for saving resources [3].

The aim of this thesis is therefore to show SMEs a way to enable first steps towards sustainable production with limited financial resources, simple technical solutions and with the help of low-code platforms. For this purpose, a real-time digital CO_2 twin of a machine is created, which makes it possible to derive the Product Carbon Footprint (PCF) of a product based on the individual production steps.

1.1 Definition and Limitation

"A product carbon footprint balances all greenhouse gas emissions – related to a defined unit of benefit – that occur during the life cycle of a product" [4]. All process steps are taken into account – from the development, manufacture and transport of raw materials to production, use and disposal of the product [5].

Depending on the system boundaries, however, only certain parts of the life cycle of a product can be recorded. In the business customer (B2B) sector, often only the part that includes emissions from production and the precursors required for this is taken into account [6]. This means that emissions are calculated from the procurement of raw materials to the completion of the product, but the use and disposal by the end customer are excluded. This method is called cradle-to-gate (from the origin to the factory gate) [7].

In the field of consumer trade (B2C), on the other hand, the path of the product to the sale to the customer is often also taken into account [6]. In addition to production, the emissions caused by the transport and storage of the product before it ends up in the store or online shop are also recorded. This ends at the so-called point of sale [6].

Another option is the cradle-to-grave approach (from origin to disposal), which looks at the entire life cycle of a product. This includes not only the emissions from production and transport, but also the emissions during use and finally those during the disposal of the product. This method provides a comprehensive view of a product's environmental impact [8].

1.2 Standards and Frameworks

The calculation of a product's carbon footprint is regulated by various international standards. Among the most well-known are PAS 2050, the Greenhouse Gas Protocol and ISO 14067.

The Publicly Available Specification (PAS) 2050 was developed by the British Standards Institution (BSI) in 2008 and revised in 2011. It offers one of the first internationally applicable frameworks for quantifying greenhouse gas emissions along the life cycle of products and services. Its goal is to provide companies with a clear indicator to evaluate and compare the environmental impact of products [9].

The Greenhouse Gas Protocol, published in 2011 by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), builds on PAS 2050 and aims to provide internationally valid guidelines for calculating and reporting product-related CO_2 emissions, while at the same time identifying emission reduction potential, especially for companies [9].

ISO 14067, first published in 2013 and updated in 2018, provides standardized rules for calculating and communicating the carbon footprint of products. It is based on several ISO standards such as life cycle analysis (ISO 14040 and ISO 14044). According to the standardised calculation of the PCF, the standard allows it to be communicated in order to enable comparability between similar products [10].

All three standards pursue the goal of systematically recording the greenhouse gas emissions of products and making them comparable in order to enable more sustainable decisions along the value chain.

1.3 Methodology

A Life Cycle Assessment (LCA) is required as a methodological basis for the PCF according to ISO 14067 [11]. Based on the LCA, each section of the product life cycle is subjected to a process step analysis, in which the individual process steps are recorded and the associated data is analyzed. This process is shown as an example for an example aluminium product in Fig. 1. For each life cycle of a product, a detailed process step analysis is required. In this analysis, the entire cycle is divided into individual process steps, with each step backed up with specific data or well-founded estimates of the consumption involved, such as energy or materials.

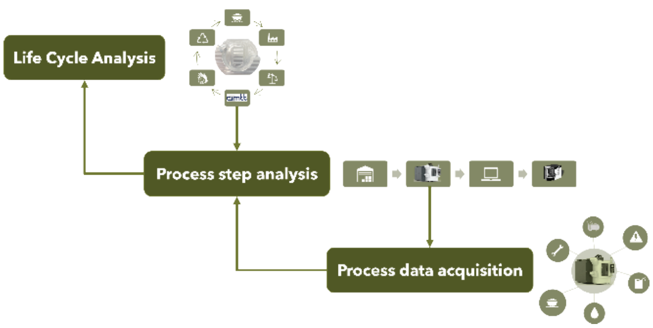

Figure 1 Life cycle analysis of the product [Own figure, CC]

2 LIFE CYCLE ANALYSIS

In this chapter, an initial estimation of an LCA is explained on the basis of an example product in order to systematically derive a PCF from it. The individual steps of the process are described in detail with the help of an LCA and process step analysis and the relevant data sources and calculation methods are shown. The section of an LCA described here does not claim to be complete and serves only as an initial orientation and should be carried out holistically and software-supported in accordance with the applicable regulations.

2.1 The Life Cycle

The calculation of the PCF is based on a comprehensive LCA that covers all phases of the product life cycle. The transport routes and means between the individual cycles are also taken into account. The cradle-to-grave approach is followed for the product. Starting from the extraction of resources, through the manufacture, production and processing of the aluminium, to the disposal or recycling of the product, the entire life cycle is thus considered, which is schematically shown in Fig. 2.

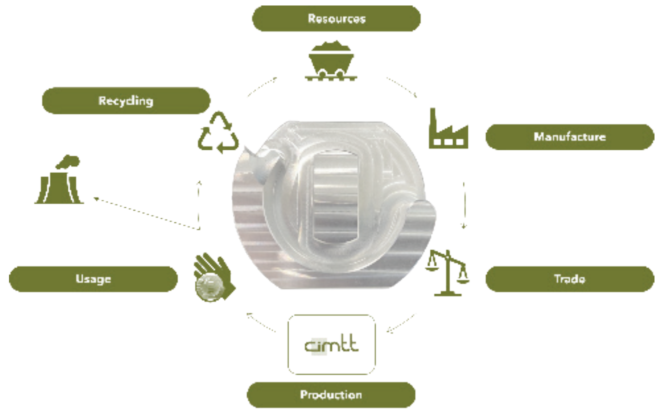

Figure 2 The life cycle of the product

If the composition of the aluminium used is not known, the assumption is followed that it is pure aluminium without recyclate content. This marks the beginning of the life cycle in the extraction of bauxite, which is converted into raw aluminium using energy-intensive chemical processes. The raw aluminium is shipped to Europe for further processing, where it is formed into round bars, heat treated and then made available to customers at dealers. From there, these are delivered to the producers and processed into individual products. The life cycle of the product ends with the use of the dispensers and their subsequent return to the recycling cycle.

2.2 Process Step Analysis

The step of process step analysis is illustrated by the life cycle section of production. Within this cycle, various process steps take place, which can be easily traced, especially in terms of measurement technology. This enables precise recording of the relevant consumption data and a detailed mapping of emissions in the individual phases of the production cycle.

The production process includes the transformation from the aluminium round bar to the finished, individualised product. An overview of these production steps is schematically shown in Figure 3.

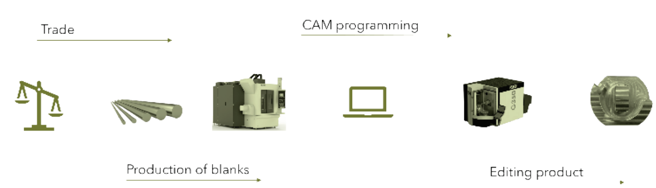

Figure 3 Process steps of production for the product

The purchase of the aluminium round bars and their transport to the production hall mark the beginning of the life cycle stage in production. In a first step, the round bars are divided into blanks with a diameter of 50 mm and a thickness of 20 mm on a lathe. Subsequently, students model and individualize the adhesive tape dispensers as part of courses. The necessary CNC programs for machining are also developed. In a further step, the blanks are processed and finished on another machine using these CNC programs. This process step concludes the considered life cycle section before the product enters the use phase.

2.3 Process Data Acquisition

According to the methodological approach, the individual process steps must be analysed with regard to their resource consumption and the associated emissions. Especially when using machines, comprehensive collection of machine data forms the basis for the assessment of product-related greenhouse gas emissions. Fig. 4 serves as a first guide to identify the basic data for the calculation of the PCF.

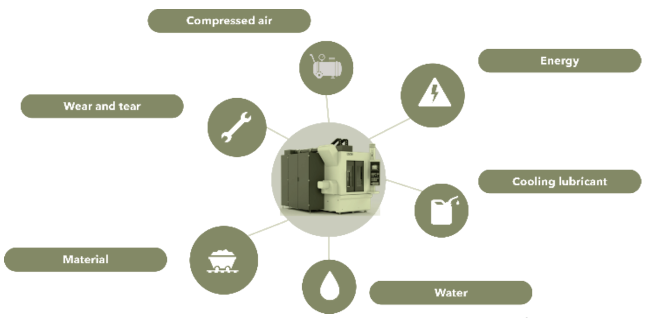

Figure 4 Exemplary data collection to determine an MCF

The recorded machine data includes not only energy consumption in the form of electricity, but also the consumption of operating resources such as materials, water, compressed air and cooling lubricants. In addition, the emissions generated during the manufacture of the machines themselves and from wear and tear, for example of the tools, must be taken into account proportionately. The collection of this data can be done with limited financial and technical resources. If this data is not immediately available, realistic estimates or observations are used first.

2.4 Calculation

The determined consumption data is linked to emission factors to calculate the CO_2 equivalent. These emission factors, which are stored in databases such as those of the Oeko-Institut e.V., the European Environment Agency (EEA) or the ProBas database of the Federal Environment Agency, relate to materials, means of transport and production processes. They include not only CO_2, but also other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O) and fluorinated gases.

The collected emission factors are processed in a spreadsheet program or appropriate software (such as Open LCA), with specific values calculated for each process step identified in the Life Cycle Analysis (LCA). The calculation is made by multiplying the consumption data by the corresponding emission factors to determine the greenhouse gas emissions in CO_2 equivalents. The calculated emissions are then aggregated to determine the product-specific CO_2 footprint.

3 TECHNICAL IMPLEMENTATION

Below, the focus is on the technical process for creating the PCF for the product. The focus here is on the production steps and the real-time recording of machine data in production. From this, a so-called CO_2 twin of the machine is determined in order to derive the product-specific PCF. For this purpose, the machines used are described and the relevant consumption data – such as energy, cooling lubricants, material and compressed air – is recorded with the help of sensors. In addition, estimates of machine wear, tool use and water consumption are made.

The collected data is processed, stored and visualized using open source software (OSS). On this basis, the specific consumption of the product is derived, including both reference runs and estimates. Finally, the consumption data is processed in a calculation tool in order to calculate the product-related greenhouse gas emissions with the help of the emission factors.

3.1 Machine Carbon Footprint

The CO_2 twin of a machine includes all CO_2 equivalents that are generated in connection with the machine. The focus is on dynamic consumables such as energy, coolants and compressed air, while also taking into account static values, such as emissions from the machine's manufacture. To this end, a large amount of data relating to the machine is recorded and supplemented with estimates and assumptions. The recorded data is processed, stored and then visualized so that real-time monitoring is possible.

The consumption data is measured and calculated directly as CO_2 equivalents. This allows an efficient derivation of the PCF by analyzing the machine carbon footprint (MCF), as well as by reference runs. At the same time, the CO_2 consumption of the respective machine is monitored in real time, see Fig. 5 below.

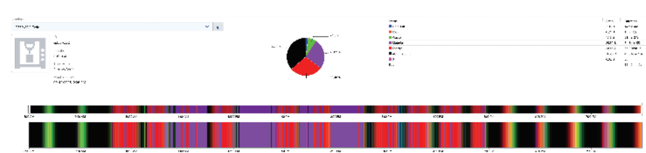

Figure 5 Machine carbon footprint as a CO_2 twin in the cloud.

3.2 Data acquisition and sensor technology

For the real-time monitoring of consumption during the production steps, a machining center from Chiron and Grob is used. Both machines are equipped with various sensors that record electricity, compressed air, cooling lubricant and the material used. The collected data is processed, stored and then visualized on various platforms.

Current measurement is carried out via three-phase current clamps of the Shelly brand. These are mainly used in the home automation sector on photovoltaic systems. The implementation is machine-independent and cost-effective. These sensors record the entire electrical load of the machines directly at the power supply. All three phases of the machine are recorded and approved.

Flow sensors from Emerson are used for compressed air monitoring. These sensors work on the basis of a hot-wire anemometer, which measures the flow based on the temperature difference of a heated wire.

The coolant consumption is recorded by a specially developed monitoring system, which monitors the level of the coolant tank as well as the temperature and pH value. The measured values are recorded by temperature sensors, an ultrasonic sensor and a pH sensor and merged and forwarded on an ESP32 microcontroller.

The material consumption is recorded on an order-related basis via a smart scale. Here, the blank is weighed before and after machining to determine the exact amount of material consumed. For this purpose, the material used is specified in order to correctly allocate the consumption and determine the amount of chip waste.

Water consumption is not yet measured directly. Instead, an estimate based on the weekly refill quantity is used and calculated down to the measurement period so that the estimated values can be transmitted in accordance with the real consumption data.

The CO_2 emissions caused by the production of the machines are treated in a similar way. An assumed, fictitious CO_2 value for machine manufacturing is broken down in time on the basis of the depreciation tables (AfA) and taken into account on a pro rata basis. An estimate for tool wear is also made. Here, the average service life of the tools is used as a guideline to determine the approximate material consumption. However, since the tools are only used sporadically in the production process, this component is not further considered in the present analysis.

All sensors, scales and monitors are able to send their collected data to an MQTT broker at an individually definable interval. This structures the information from the various sensors under the respective topics and makes it available for further processing. The machine data as well as current values are sent to the database every second. The flow of compressed air is sent every 100 ms.

3.3 Data Processing

The collected data from the machines is sent in real time to a central MQTT broker via the MQTT protocol. The broker is managed by a Node-Red instance installed on an industrial PC (IPC). Node-Red acts as an interface for data processing. The incoming sensor data is sorted in Node-Red according to its respective MQTT topics and merged into a message object and stored. In this step, the recorded consumption is retrieved every 10 seconds to ensure a uniform and precise database. In addition, the CO_2 equivalents for the measured consumption are calculated here by applying the appropriate emission factors to the data and adding them to the news object as further information.

The message object is then sent to an InfluxDB database that is also installed on the IPC. InfluxDB is an open-source database optimized specifically for time series data, which makes it possible to efficiently store and manage large amounts of continuously incoming data. The data is stored in so-called "buckets" (similar to databases) and structured in "measurements" (similar to tables). Within the measurements, the data points are displayed in "Fields" (columns) [12]. In addition, data points are tagged with "properties" so that later filtering and analysis according to certain criteria is possible.

3.4 Data Visualization

For an initial visualization of the collected and processed data, the InfluxDB UI offers an integrated query builder. This makes it possible to perform data queries without in-depth knowledge of the Flux query language, which means that the database can be understood as a low-code solution. In this way, relevant consumption and CO_2 data can be clearly displayed and further processed in order to gain deeper insights into machine performance and machine-related CO_2 consumption.

Another visualization of the collected machine data is done with the help of the open source software Grafana, which enables a flexible and customizable display. Grafana supports the integration of a wide range of data sources, including InfluxDB, and provides a user-friendly interface to present the stored data in a clear and interactive way. Once the InfluxDB database is linked to Grafana, the data can be visualized in the form of graphs and dashboards.

Visualization is done via Flux queries that access the data stored in the InfluxDB. This allows each graph to be individually designed and adapted to show various consumption parameters and CO_2 emissions in real time. In addition, the use of variables within the dashboard allows for flexible adjustment, for example to visualize the consumption data of different machines.

Another feature of Grafana is the ability to integrate thresholds and KPIs (Key Performance Indicators) directly into the visualizations. In this way, critical thresholds or targets can be clearly displayed in the dashboards. This not only enables real-time monitoring of machine data, but also the immediate identification of inefficient processes or exceeded consumption limits to ensure proactive process optimization.

In addition, the consumption data is forwarded to a cloud of the company Grob, so that in addition to the information from the machine, the consumption data of the resources but also the CO_2 are visualized.

3.5 Determination of the PCF

To determine the PCF, the recorded consumption values are now retrieved from the database. For this purpose, it is necessary to know the exact time of production and to carry out reference runs for the individual processing steps. For product-related tracking, consecutive product numbers must be carried in addition to consumption, so that a clear assignment is possible. For the entire PCF, the data is divided into two categories: static and dynamic values.

Static values are emission data that cannot be influenced by the production process itself. They refer to all emissions that occur before and after the actual production, such as through raw material extraction, transport and disposal. In order to enable a precise accounting of these emissions, a detailed research of the corresponding emission factors is required. These factors, such as those stored in databases such as ProBas, must be applied to the real reference masses and transport routes. An example of this is the calculation of the CO_2 equivalent for the aluminum used to manufacture the product. Based on the weight of the product, the specific CO_2 equivalent for aluminium production is determined by converting the weight of the product to the reference value of the emission factors (usually per tonne) and multiplying it by the corresponding factor.

Dynamic values are real-time measurement data collected and can be assigned directly to the respective processing steps. This data is determined either by reference runs or by measuring individual manufacturing processes. Therefore, there are two approaches to incorporate the dynamic data into the PCF of the product: Either the production of a single product takes place in each process step and the corresponding consumption is directly assigned, or a larger number of dispensers is produced from a material batch and the consumption is distributed among the manufactured units.

For the final determination of the CO_2 equivalents, all determined consumption data, estimates and assumptions are collected and offset against the respective emission factors. For an initial assessment of the PCF, it is sufficient to implement it in Excel or another suitable spreadsheet tool. Another possibility of implementation is in the open source software "openLCA". This enables a process-oriented recording and collection of all emissions with the help of stored databases.

Finally, all recorded, estimated and assumed consumption values are summed up to calculate the total PCF of the dispenser. The PCF thus represents a comprehensive representation of the emissions that occur over the entire life cycle of the product.

3.6 Evaluation

The CO_2 footprint of the product over the entire life cycle is about 4.5 kg CO_2. This is roughly equivalent to the volume of 2,400 milk cartons filled with CO_2 [13]. From this initial estimate, the main sources of emissions are the extraction and production of the aluminium used, which accounts for 51% of the total, and the production of the dispenser itself, which accounts for about 27% of emissions. The remaining 22% is divided between transport, use and recycling of the product. When looking at production, it can be seen that electricity consumption accounts for 55% and compressed air for 44% of the carbon footprint. The calculation results are summarized in Fig. 6.

The example of the product shows that the greatest savings potential lies primarily in the choice of raw materials and production. In production, the shares make it clear that optimizing energy use is a key lever for reducing the CO_2 footprint. By using sustainably generated electricity, 19% of emissions are saved, as this electricity usually has an emission factor of zero. However, the much greater influence on the CO_2 footprint is the choice of raw material. The use of recycled aluminium significantly reduces the footprint, as recycled aluminium requires only about 5% of the energy required compared to primary production [14]. This, in turn, leads to a reduction in the overall footprint of up to 38%.

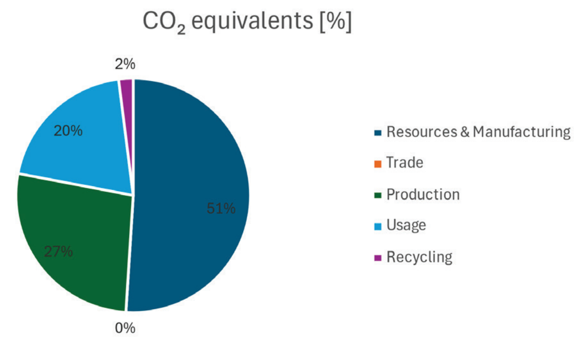

Figure 6 Percentage distribution of emissions by life cycle

These results show that a shift to greener materials and energy sources can have a significant impact on reducing the carbon footprint and provides a basis for strategic decisions to reduce greenhouse gas emissions.

4 CONCLUSION

In the context of this paper, a Product Carbon Footprint was created for an example product. First, the regulatory requirements and framework conditions were examined and a methodology for the systematic preparation of the PCF was developed. This was followed by an initial life cycle analysis, in which all phases of the product life cycle were analysed and supplemented by a process step analysis. Both process data and well-founded estimates were included in the evaluation. A central aspect was the implementation of a CO_2 twin of the machine. With the help of sensors, consumption such as electricity, compressed air, cooling lubricants and materials were monitored in real time in order to record, store and visualize the CO_2 consumption of the machines in detail. This data forms the basis for the precise determination of the production-specific CO_2 footprint of the product.

The aim of this work and the machine carbon footprint was to show how the PCF can be integrated into existing production environments in a cost-effective way. This data can be used to identify optimization potential in order to take targeted measures to reduce the CO_2 footprint.

In addition to improving resource efficiency, the PCF supports companies in preparing for future regulatory requirements at an early stage, so that the data contributes to the long-term optimization of the company's environmental balance. Another advantage of the determined production data is the increased transparency within production. They serve as a basic building block for estimating the possible CO_2 emissions even before production begins. Companies are thus able to choose production processes with regard to lower CO_2 emissions or to design them in such a way that resources are used more efficiently and that they implement targeted measures to reduce emissions and reduce costs. In this context, it is necessary to examine the influence of a reduction, e.g. of the KSS on product quality as well as the PCF. This work thus promotes continuous improvement of production processes and contributes to more sustainable production.

5 REFERENCES

[1] "Greenhouse gas emissions by sector in Germany 2023", Statista. Accessed: December 18, 2024. Available at: https://de.statista.com/statistik/daten/studie/1241046/umfrage/treibhausgasemissionen-in-deutschland-nach-sektor/ (in German)

[2] Wilke, S. (2024). *Indicator: Greenhouse Gas Emissions from Industry*. Federal Environment Agency. Accessed: December 18, 2024. Available at: https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-treibhausgas-emissionen-der-industrie (in German)

[3] Schroedter, F. (2023). *The Impact of CSRD on Companies: A Comprehensive Overview*. Engel & Zimmermann. Accessed: August 23, 2024. Available at: https://engel-zimmermann.de/blog/die-auswirkungen-der-csrd-auf-unternehmen/ (in German)

[4] *Carbon Footprint - IZU*. Accessed: October 1, 2024. Available at: https://www.umweltpakt.bayern.de/energie_klima/fachwissen/279/carbon-footprint (in German)

[5] Gacs, J. (2024). *What is a PCF? | How companies use the Product Carbon Footprint*. Green Vision Solutions GmbH. Accessed: February 4, 2025. Available at: https://greenvisionsolutions.de/blog-product-carbon-footprint/ (in German)

[6] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), ed. (2010). *Product-related climate protection strategies Product Carbon Footprint verstehen und nutzen*. Available at: https://bdi.eu/media/presse/publikationen/PCF-Leitfaden_100810_Online.pdf (in German)

[7] *Greenhouse gas protocol: product life cycle accounting and reporting standard*. Washington, DC, Geneva, Switzerland: World Resources Institute; World Business Council for Sustainable Development, 2011.

[8] *"life cycle assessment"*. European Environment Agency. Accessed: October 2, 2024. Available at: https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment

[9] ghgprotocol.org, ed. (2011). *QUANTIFYING THE GREENHOUSE GAS EMISSIONS OF PRODUCTS PAS 2050 & the GHG Protocol Product Standard*. Available at: https://ghgprotocol.org/sites/default/files/ghgp/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf

[10] Ullrich, A. & Gronau, N. (2021). Norms for the Calculation of the CO_2 Footprint. *Ind. 40 Manag., 2021*(4), 17-20. https://doi.org/10.30844/I40M_21-4_S17-20

[11] Pandey, D., Agrawal, M. & Pandey, J. S. (2011). Carbon footprint: current methods of estimation", *Environ. Monit. Assess., 178*(1-4), 135-160. https://doi.org/10.1007/s10661-010-1678-y

[12] *InfluxDB key concepts* | InfluxDB OSS v1 Documentation. (2015). Accessed: February 4, 2025. Available at: https://docs.influxdata.com/influxdb/v1/concepts/key_concepts/

[13] *What kind of volume does CO_2 actually have?* Accessed: October 16, 2024. Available at: https://www.gasag.de/magazin/nachhaltigkeit/CO₂-volume/

[14] Frischenschlager, H. et al. (2010). *Klimarelevanz Ausgewählter Recycling-Prozesse in Österreich*. umweltbundesamt. https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0303.pdf (in German)

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RFID-Enabled Smart Manufacturing: Real-Time Asset Tracking and Operational Workflow Optimization

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Abstract: The article presents the possibility of implementing an RFID system to increase transport efficiency in both classic industrial environments and in infrastructure with a high level of automation. The proposed solution takes into account the possibility of installing RFID readers on poles, suspended ceilings, as well as in the floor of the storage and communication space. Thanks to its universal approach and scalability, it allows to increase the level of process automation, especially in SMEs. The implementation of the proposed system in modern factories will make it possible to track in real time the location of products and materials required for production and will have a positive effect on optimizing the flow of these objects within the production environment. Moreover, the implementation of this system is affordable for most enterprises.

Keywords: Industry 4.0; internal traffic management; Internet of Things; production management; RFID

1 INTRODUCTION

The role of smart factories and intelligent warehouses is becoming increasingly pivotal in the context of a rapidly evolving industrial landscape. Modern enterprises are progressively integrating advanced automation solutions to optimize production processes and enhance operational efficiency. In this regard, the implementation of state-of-the-art systems leveraging technologies such as Radio Frequency Identification (RFID) and the Internet of Things (IoT) is gaining significant traction [1-5]. However, the widespread adoption of these technologies remains constrained primarily by the substantial financial investment required for their deployment within contemporary manufacturing environments. While numerous cutting-edge solutions have demonstrated the potential to significantly enhance production efficiency and streamline inventory management in warehouse settings, financial constraints often pose a substantial barrier to their large-scale implementation, particularly for small and medium-sized enterprises (SMEs) [6]. This challenge underscores the need for cost-effective, scalable solutions that bridge the gap between conventional warehouse management practices and fully autonomous systems, facilitating gradual digital transformation in industrial operations. Solutions that will significantly impact overall operational efficiency with the minimum of impact on existing infrastructure will be in demand in the industry.

The SME sector is a large market that should also be given a chance to participate in the evolution of the industrial landscape. Is it feasible to apply modern Industry 4.0 technologies to warehouses and production facilities without the need to invest enormous amounts of money to entirely overhaul the existing space? The aim of the system outlined in this paper is to ensure a sufficient level of automation in warehousing and manufacturing environments belonging to the SME sector. The proposed system combines affordability and the advantages of automating object tracking and identification processes, providing an ideal solution for SMEs.

Section 2 presents a literature review of existing solutions applicable to modern warehousing environments. Section 3 discusses the proposed solution considering the measurement methodology and a characterization of the research environment. Section 4 is an overview of the results obtained and a discussion of the capabilities of the proposed system.

2 CURRENT APPLICATIONS OF ADVANCED TECHNOLOGIES IN THE FIELD OF SMART FACTORIES AND WAREHOUSES

The adoption of numerous technological solutions in smart warehousing and manufacturing environments is particularly prevalent among technology giants. Small and medium-sized enterprises try to keep up with technological changes and implement them gradually. However, this kind of companies do not have the same financial resources as larger enterprises. The implementation of solutions incorporating various robots and automation-supporting devices requires multimillion-dollar investments posing a significant challenge, especially in the SME sector. The warehouse environment management systems used by tech giants such as Amazon and DHL use autonomous mobile robots (AMRs) to increase operational efficiency. SME companies do not have the financial capacity to fully automate their warehouse environments with this sollutions.

2.1 RFID and IoT in Smart Warehouses

The most advanced technologies have been applied for many years to digitally transform warehousing and manufacturing environments. The cited studies have demonstrated that since 2010, the implementation of technologies such as automated vehicles and Internet of Things devices in warehouses increases space utilization by 15% and reduces order picking time by 10% [1]. The use of RFID technology in these environments increases operational efficiency, which is particularly significant in the FMCG sector [7]. Automated Guided Vehicles (AGVs) are also utilized in intelligent warehousing and production environments, despite the considerable costs associated with procuring such devices. Integrating these robots with RFID capabilities enables a more automated and efficient management of AGVs within warehouses. Proper placement of RFID transponders in such environments facilitates the precise determination of an AGV's position [2]. Additionally, equipping AMRs with supplementary modules that leverage computer vision allows for accurate assessment of inventory levels in a given warehouse environment [6]. The integration of all these devices and robots with IoT capabilities enables real-time responses to various factors, such as new orders or the need to replenish inventory, thereby optimizing processes and increasing product throughput [3].

2.2 Multi-Agent Systems and Robotics in Industry 4.0

In intelligent warehousing and manufacturing environments, it is possible to also use multi-agent cyber-physical management systems, which, combined with RFID technology, enable precise monitoring of warehouse inventory levels, and reduce the likelihood of human error. A simulation demonstrated that the implementation of such systems in a cryogenic warehouse significantly reduces the dwell time of materials in the system. Depending on the stage, the time was reduced from 38.46% to 58.23% [4]. Corporations such as Amazon and DHL are currently employing numerous robots in their logistics centers to improve operational efficiency. The use of robot swarms in these environments makes it possible to perform tasks that individual units would not be able to accomplish - for example, the movement of a 1-ton load by two robots with a lifting capacity of 500 kg each [5]. In these environments, preventing collisions between autonomous robots is also of utmost importance. In this regard, agent-based modelling is proving useful, whereby each robot is able to communicate with the others thereby supporting dynamic decision-making and preventing collisions [8]. The integration of such solutions with RFID capabilities presents a significant challenge, as the RFID network must be properly planned to avoid network overloads and reduce interference. Intelligent swarm optimization algorithms such as Particle Swarm Optimization are instrumental in the planning of RFID networks efficiently [9].

2.3 Digital Twins and Intelligent Manufacturing Analysis

During the complex stage of production, the early detection of possible production errors and their elimination is of paramount importance. To achieve this, the implementation of systems that enable precise monitoring of the position of a given product on conveyor belts is highly beneficial. These systems include the digital twin model, which, in conjunction with an RFID network deployed within a real manufacturing environment, facilitates the accurate location of products, regardless of conveyor speed [10]. The implementation in manufacturing environments of intelligent systems that use deep belief networks to make crucial decisions such as controlling CNC machine tools positively impacts production efficiency and provides the lowest prediction error among those tested [11]. Industry 4.0 technologies including RFID and Sigfox likewise enable more efficient production through reduced waiting times between manufacturing steps. This improvement is made possible by automated and continuous monitoring of product flow [12]. Moreover, the analysis of data acquired from RFID systems in such manufacturing environments facilitates more precise operational decision-making as well as the identification and elimination of rate-limiting steps. This approach significantly improves operational efficiency as well as reduces production errors [13, 14]. Solutions of this sort, based on Industrial Internet of Things (IIoT) devices, significantly facilitate the optimization of production planning and scheduling. The use of wireless sensor networks in manufacturing environments provides a sizable amount of data for analysis and enables dynamic decision-making [15]. Furthermore, the role of RFID-based systems is crucial in modern factories and smart warehouses. In addition to optimizing processes, the analysis of data collected by RFID readers also enables the acquisition of decision rules that can be used for better production planning [16].

2.4 Internal Location and Navigation Systems

One of the mainstream and widely used solutions implemented in modern factories and smart warehouses are certainly Real Time Location Systems (RTLS). The integration of these RTLS with Manufacturing Execution Systems (MES) is crucial for optimizing manufacturing processes [17]. Radio Frequency Identification technique could also be used in the RTLS. Placing RFID transponders in all stationary objects in warehousing or manufacturing environments, along with storing the data about the coordinates of a given transponder and the type of surface, creating a grid of the room concerned is feasible. Furthermore, by placing an RFID reader on the AMR, it is possible to precisely locate the robot in the warehouse environment and prevent collisions [18, 19]. Additionally, the usage of innovative RFID-SLAM technology is suitable for mapping warehouse spaces. Application of this technology in a 35 m^2 research environment has demonstrated an average robot localization error of less than 5cm and an average error in estimating the three-dimensional localization of RFID transponders placed in the research environment of approximately 10 cm [20].

2.5 Smart City and Traffic Management

Nowadays, the use of advanced technologies for traffic management is an essential element of the Smart City 2.0 concept. The application of RFID technology integrated into the road infrastructure or directly within the vehicles provides not only traffic flow monitoring and vehicle identification, but in addition enables dynamic control of traffic flow. This approach significantly improves the efficiency of vehicle movement through smart cities [21]. Extending this kind of solution with 5G technology and cloud computing, urban traffic management is becoming more scalable. Communication between numerous vehicles permits automatic detection of parking space occupancy. This solution facilitates more efficient management of parking infrastructure and reduction of the travel time [22]. Implementing comparable technologies and algorithms in smart warehousing environments would be expected to result in more efficient placement of products on warehouse racks.

3 RFID-ASSISTED INTELLIGENT TRAFFIC MANAGEMENT FOR INTERNAL LOGISTICS IN MODERN FACTORIES

The RFID technology is deployed in nearly all identification systems designed for smart warehouses. This is due to its advantages, particularly operating costs comparable to those incurred when using barcode-based systems. However, in contrast to barcodes, the use of RFID systems is more efficient and less sensitive to weather conditions. The UHF RFID technique makes it possible, using appropriate algorithms that take into account the capture effect, to read up to 1,000 objects once during a single measurement cycle with an identification error of less than 2% [23]. The proposed solution primarily uses RFID-based systems while considering the lowest possible implementation costs to enable SMEs to modernize their manufacturing and warehousing environments. The implementation of this system in modern factories will make it possible to track in real time the location of products and materials required for production and will have a positive effect on optimizing the flow of these objects within the production environment. The developed solution is a connectivity solution that allows SME enterprises to provide a quality of service at a level similar to large international corporations taking a full advantage of available technological solutions. Although this solution will never be better than fully automated environments it certainly is attractive to the SMB sector. Such a solution represents an ideal balance of implementation costs and potential advantages in the context of overall operational efficiency.

3.1 Overview of the Employed Technology

During the conducted measurements of the system for identification and tracking of objects in warehousing and manufacturing environments, an array of RFID readers based on the PN532 controller operating at a frequency of 13.56 MHz has been used. These short-range readers fulfilled their function placed on the prepared mock-up of the measurement environment. However, in case of implementing the solution in smart warehouses, their range will be insufficient. In manufacturing environments, it would be required to use industrial solutions. The appropriate RFID UHF readers for such implementations are those compatible with EPC Class1 Gen2 transponders in accordance with ISO/IEC 18000-6C standard. Real-world tracking capabilities will be made more efficient due to the capabilities of UHF RFID readers, particularly the ability to read numerous transponders during a single read sequence.

In order to measure the efficiency of object identification and tracking, customized cubes were produced, printed using FDM additive manufacturing technology, in which RFID transponders were implemented. The RFID cubes were designed in two different variants: with the transponder implemented inside the cube during the additive manufacturing process, and with the transponder placed on the outer wall in a small dimple. The appearance of the cubes is shown in Fig. 1.

The same type of RFID transponder in the form of NFC NTAG213 stickers has been placed in both variants of RFID boxes. The tests conducted revealed that the type of RFID cubes does not affect the efficiency of identification. In other words, the transponders can be implemented into the product at the production stage and may not be visible as in the case of barcode-based systems. The solution provides efficient and low-failure identification of objects, and ensures that product batches are marked in a secure and difficult-to-defect method. The placement of RFID transponders inside products at the manufacturing stage ensures that any attempt to defect the RFID tag will end up with damage to the entire product. This approach provides greater security in product identification and reduces the risk of misidentification.

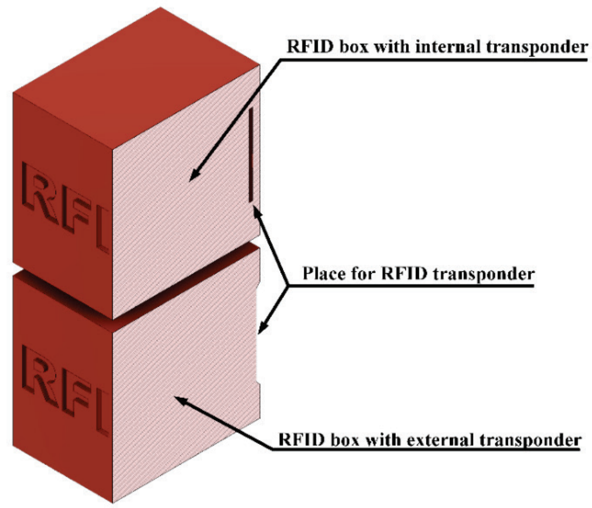

Figure 1 RFID cubes prepared for measurements

3.2 Concept of Asset Tracking and Operational Workflow Optimization System

The primary objective of the concept presented was to provide the SME sector with a solution that would enable real-time object tracking and improve operational efficiency. An additional requirement was the simplicity of implementation and relatively inexpensive implementation and operating expenses, so that smaller enterprises would have the opportunity to implement such a system. Another important aspect is the approachable scalability of the proposed solution. During the design process for a suitable solution, the principal problem that was identified in operational efficiency contexts were the intersections that occur in warehousing and manufacturing environments. These intersections are locations where the utmost caution is required of the operator, and thus the need to reduce travel speed. This is particularly relevant in environments where the space allocated to warehouses or production lines has been expanded compared to the transportation area between these zones. Fig. 2 demonstrates a conceptual layout of part of such an environment. In (a), a diagram representing the various processing zones and storage facilities is provided. In (b), a visualization of a mock-up prepared for measurements to verify the operation of the system is illustrated. This is a diagram of a production environment with integrated warehouses for current production needs. The final environment may consist of numerous such parts, with many more processing zones and their associated warehouses. With an increased number of zones, the number of intersections in the entire manufacturing environment will also be increased. The increase in the number of intersections will directly affect the transit time from point A to point B. The need to cross the numerous intersections will be a multiplier of the time spent traveling through a single intersection. Therefore, the larger the warehouse environment, the more intersections between avenues in the environment, which leads automatically to much higher delays. A delay of for instance 5 seconds at an intersection may look inconspicuous, however, multiplied by 12 intersections, it already gives 60 seconds per trip. Calculating that a transport truck takes such a route 60 times a day, the time savings on the entire cycle is one hour per day.

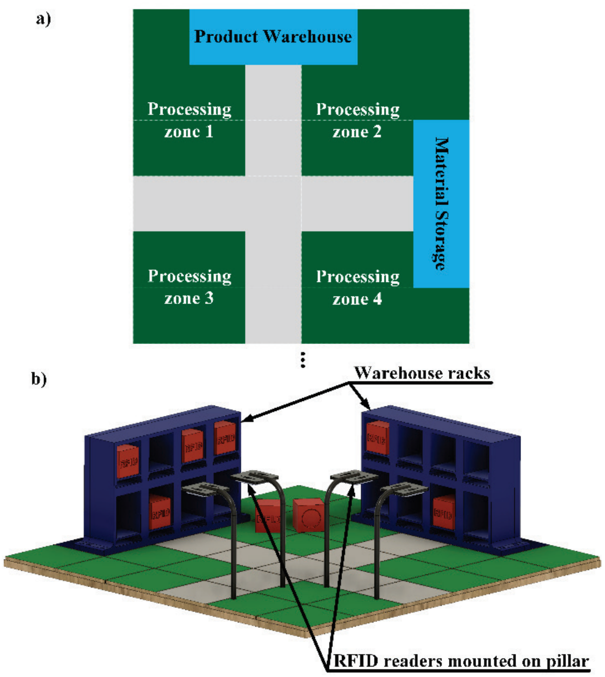

Figure 2 Conceptual representation of a production environment: (a) layout of the manufacturing eniviroment, (b) visualization of the measurement environment

3.3 Prepared Measurement Environment

In the test environment thirty-six identical fields have been located, with an RFID reader based on the PN532 controller implemented under each of them. The array of these readers can be expanded with additional modules placed on poles. The placement of these readers in the described locations would not directly affect the efficiency of the system for tracking objects in the environment. However, the placement of RFID readers in the ground requires a much more invasive renovation and spatial adjustment, which involves more financial investment. Installation of readers on poles, or if possible, directly to the ceiling in a manufacturing environment provides a more cost-effective solution. The mock-up of the research environment is shown in Fig. 3. The entire environment was made of fabrics that do not interfere with the radio waves used by RFID technology. The testing environment also includes two standalone racks each equipped with separate RFID readers for real-time monitoring of inventory levels. In Fig. 3, the research environment is configured to use RFID readers placed in the base. Several of these devices have been exposed for a more transparent demonstration of the prepared mock-up.

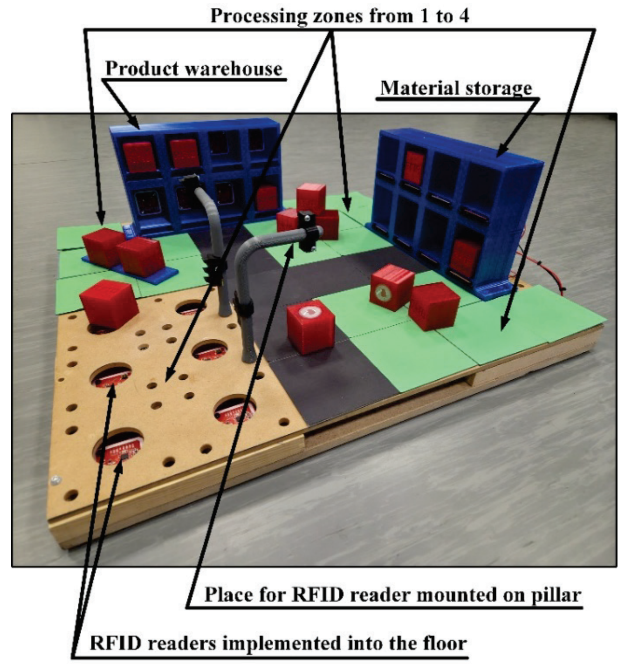

Figure 3 The mock-up of the measurement environment

All of the RFID readers of the research environment were connected to a Raspberry Pi microcomputer using pin multiplexers. The mock-up of the warehouse environment presented is a single system cluster consisting of a control unit and 36 RFID readers with the possibility of expanding with additional readers. Implementation of the solution in smart manufacturing environments requires the use of several clusters. Readers inside one cluster are run sequentially, therefore the higher the number of readers per control unit, the longer the time of one measurement cycle. However, using several clusters, it is possible to run individual zones of a warehouse or production environment independently. Such a solution increases the efficiency of product tracking by enabling several clusters of the system to run the measurement cycle in parallel. Moreover, this type of system is more resilient to setbacks, the breakage of one reader locks up the tracking system in one cluster instead of the entire environment.

3.4 Methodology

In order to make the measurements available, it was necessary to make several assumptions. One such assumption was the time it takes for a vehicle to cross an intersection without the impact of external factors. Based on this assumption, it was possible to calculate the remaining time data in the case of the sequential algorithm. With the knowledge of the time of physical crossing of the intersection and the time of individual traffic cycles in the environment using the sequential algorithm, the average results of crossing and waiting times for such an environment were calculated. In the case of an environment using an RFID-based algorithm, RFID transponders were physically placed on a prepared mock-up of the measurement environment and the algorithm's response to such data was being tested. Similar to the environment based on the sequential algorithm, the crossing time was also equal to the assumed one. The only difference was the time intervals at which each traffic cycle controlled by the corresponding algorithm was launched. This approach makes it convenient to compare the performance of the algorithms themselves uninfluenced by random factors such as different crossing times or driver reaction times.

4 ANALYSIS OF RESULTS AND DISCUSSION

Research conducted on a system for tracking asset flow in warehousing and manufacturing environments has shown that it is possible to accurately track objects. The use of such a system in warehouses and factories improves operational efficiency and significantly speeds up the flow of materials within these environments.

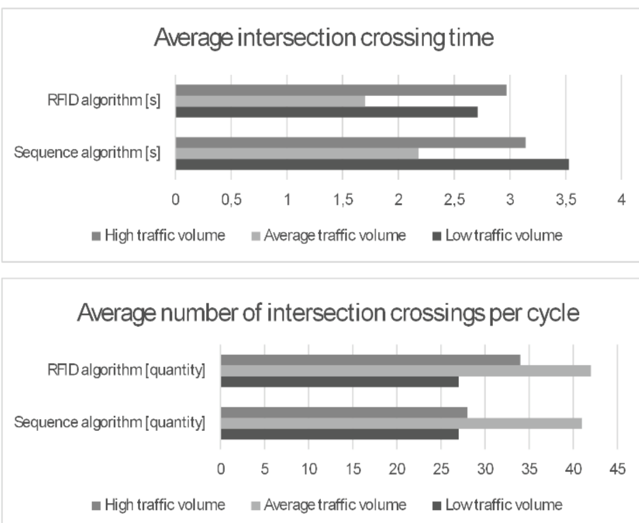

Figure 4 Charts showing the results of conducted measurements

Fig. 4 provides graphs summarizing the realized tests. The first graph shows the average crossing time at the intersection. Two control algorithms have been compared on the chart - one is a traditional sequential algorithm that allows simultaneous crossings by transport trucks from a single aisle. The other is an algorithm that uses RFID techniques to control crossing the intersection based on current demand. The traditional sequential algorithm is based on fixed time intervals assigned to each phase of intersection crossings. This algorithm is particularly inefficient during imbalanced traffic. When the flow of products is primarily through a single avenue, while traffic from another is intermittent, this algorithm will cause time delays. In these situations, the RFID-based algorithm enables dynamic control of material flow, which improves operational efficiency. The deployment of RFID readers throughout the manufacturing environment has made it possible to anticipate demand and dynamically control the flow of traffic through the intersection, thereby reducing average waiting times. With low traffic volumes, the average wait time when using the sequential algorithm was 3.53 s. This is almost a second longer than the average crossing time of 2.71 s when using the RFID-based algorithm. With increased traffic, the difference between the algorithms decreases, however, constantly using the algorithm based on RFID reader data is more efficient. The second graph shows how many average intersection crossings occur during one cycle.

The measurements showed that regardless of traffic volume, the use of the sequential algorithm was never more efficient than the use of the RFID-based algorithm.

5 CONCLUSIONS

RFID technology enables automatic identification and tracking of materials and products in real time, eliminating human errors and improving data accuracy. Thanks to integration with ERP, MES and IoT systems, it allows for intelligent management of production processes and automation of internal logistics. RFID implementation allows for dynamic adjustment of production lines in modern factories, which increases flexibility and enables rapid changes in the production and warehouse environment. Ensuring full automation and digitization of factories and warehouses involves high costs. Moreover, such implementation in an existing environment while maintaining continuity of production processes is a serious challenge. Taking into account the limitations, especially of SMEs, a solution was proposed that is scalable in its concept and can be integrated with the existing infrastructure.

The tests carried out confirm the effectiveness of the system both when installing part of the infrastructure under the floor, as well as on columns or ceiling. Additionally, the system can be expanded based on clusters, which will allow for gradual automation of existing production and warehouse spaces.

The analysis results showed that the RFID-based traffic control algorithm effectively shortens the average waiting time to pass through the intersection compared to the traditional sequential algorithm. At low traffic intensity, this difference was almost a second in favor of the RFID algorithm. With increasing traffic intensity, this advantage decreases, but the RFID algorithm remains more efficient in every situation. In addition, the number of passes per cycle was higher when using the RFID algorithm, which confirms its effectiveness. Therefore, the implementation of RFID technology in traffic control allows for the optimization of the throughput of traffic path intersections and a reduction of waiting time.

6 REFERENCES

[1] Alherimi, N., Saihi, A., & Ben-Daya, M. (2024). A systematic review of optimization approaches employed in digital warehousing transformation. *IEEE Access, 12*, 145809-145831. https://doi.org/10.1109/access.2024.3463531

[2] Zou, O., & Zhong, R. Y. (2018). Automatic Logistics in a smart factory using RFID-enabled AGVs. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM2018)*, 822-826. https://doi.org/10.1109/aim.2018.8452349

[3] Ponis, S. T., & Efthymiou, O. K. (2020). Cloud and IOT applications in material handling automation and intralogistics. *Logistics, 4*(3), 22. https://doi.org/10.3390/logistics4030022

[4] Farsi, M., Latsou, C., Erkoyuncu, J. A., & Morris, G. (2020). RFID application in a multi-agent cyber physical

manufacturing system. *Journal of Manufacturing and Materials Processing, 4*(4), 103. https://doi.org/10.3390/jmmp4040103

[5] Wen, J., He, L., & Zhu, F. (2018). Swarm Robotics Control and communications: Imminent challenges for Next Generation Smart Logistics. *IEEE Communications Magazine, 56*(7), 102–107. https://doi.org/10.1109/mcom.2018.1700544

[6] Kim, J.-A., & Jeong, J. (2018). Smart Warehouse Management System Utilizing IoT-based Autonomous Mobile Robot for SME Manufacturing Factory. *The Journal of the Institute of Internet, Broadcasting and Communication, 18*(5), 237-244. https://doi.org/10.7236/JIIBC.2018.18.5.237

[7] Pawłowicz, B., Salach, M., & Trybus, B. (2020). The infrastructure of RFID-based fast moving consumer goods system using cloud. *Advances in Intelligent Systems and Computing*, 216-226. https://doi.org/10.1007/978-3-030-40971-5_20

[8] Turhanlar, E. E., Ekren, B. Y., & Lerher, T. (2022). Autonomous Mobile Robot Travel under deadlock and collision prevention algorithms by agent-based modelling in warehouses. *International Journal of Logistics Research and Applications, 27*(8), 1322–1341. https://doi.org/10.1080/13675567.2022.2138290

[10] Demčák, J., Židek, K., & Krenický, T. (2024). Digital Twin for monitoring the experimental assembly process using RFID technology. *Processes, 12*(7), 1512. https://doi.org/10.3390/pr12071512

[11] Zhang, C., & Jiang, P. (2020). RFID-driven energy-efficient control approach of CNC machine tools using Deep Belief Networks. *IEEE Transactions on Automation Science and Engineering, 17*(1), 129-141. https://doi.org/10.1109/tase.2019.2909043

[12] Beliatis, M. J., Jensen, K., Ellegaard, L., Aagaard, A., & Presser, M. (2021). Next generation industrial IOT digitalization for traceability in metal manufacturing industry: A case study of industry 4.0. *Electronics, 10*(5), 628. https://doi.org/10.3390/electronics10050628

[13] Zhong, R. Y., Putnik, G. D., & Newman, S. T. (2021). A heterogeneous data analytics framework for RFID-enabled factories. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 51*(9), 5567-5576. https://doi.org/10.1109/tsmc.2019.2956201

[14] Feng, J., Li, F., Xu, C., & Zhong, R. Y. (2020). Data-driven analysis for RFID-enabled Smart Factory: A case study. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 50*(1), 81-88. https://doi.org/10.1109/tsmc.2018.2882838

[15] Lăzăroiu, G., Andronie, M., Iatagan, M., Geamănu, M., Ștefănescu, R., & Dijmărescu, I. (2022). Deep learning-assisted Smart Process Planning, robotic wireless sensor networks, and Geospatial Big Data Management algorithms in the Internet of Manufacturing Things. *ISPRS International Journal of Geo-Information, 11*(5), 277. https://doi.org/10.3390/ijgi11050277

[16] Ding, K., & Jiang, P. (2018). RFID-based production data analysis in an IOT-enabled smart job-shop. *IEEE/CAA Journal of Automatica Sinica, 5*(1), 128-138. https://doi.org/10.1109/jas.2017.7510418

[17] Rácz-Szabó, A., Ruppert, T., Bántay, L., Löcklin, A., Jakab, L., & Abonyi, J. (2020). Real-time locating system in production management. *Sensors, 20*(23), 6766. https://doi.org/10.3390/s20236766

[18] Skoczylas, M., Gotówko, Ł., Salach, M., Trybus, B., Hubacz, M., & Pawłowicz, B. (2022). Room mapping system using RFID and Mobile Robots. Annals of Computer Science and Information Systems, 30, 593-597. https://doi.org/10.15439/2022f248

[19] Pawłowicz, B., Skoczylas, M., Trybus, B., Salach, M., Hubacz, M., & Mazur, D. (2024). Navigation and mapping of closed spaces with a mobile robot and RFID grid. *Archives of Control Sciences*. https://doi.org/10.24425/acs.2023.148879

[20] Wu, C., Gong, Z., Tao, B., Tan, K., Gu, Z., & Yin, Z.-P. (2023). RF-SLAM: UHF-RFID based simultaneous tags mapping and robot localization algorithm for Smart Warehouse Position Service. *IEEE Transactions on Industrial Informatics, 19*(12), 11765-11775. https://doi.org/10.1109/tii.2023.3252405

[21] Pawłowicz, B., Salach, M., & Trybus, B. (2019). Infrastructure of RFID-based Smart City Traffic Control System. *Advances in Intelligent Systems and Computing*, 186-198. https://doi.org/10.1007/978-3-030-13273-6_19

[22] Pawłowicz, B., Salach, M., & Trybus, B. (2018). Smart City Traffic Monitoring System based on 5G cellular network, RFID and machine learning. *Advances in Intelligent Systems and Computing*, 151-165. https://doi.org/10.1007/978-3-319-99617-2_10

[23] Xu, W., Song, Z., Sun, Y., Wang, Y., & Lai, L. (2023). Capture-aware dense tag identification using RFID systems in Vehicular Networks. *Sensors*, *23*(15), 6792. https://doi.org/10.3390/s23156792

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Efficient Modification of the CRAFT Algorithm for Layout Optimisation

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Abstract: Every combination of product mix and production volume requires a suitable layout of workplaces (functional units). An optimised layout is of utmost importance to achieve global competitiveness of companies and to build an efficient, sustainable production. We plan the layout mainly with heuristic methods; constructive, improvement and combined methods are available. In this paper, a modification of the established improvement algorithm CRAFT (exchange method) is presented, which provides much better and more accurate results at a slightly higher computational cost. The most important change is the immediate precise determination of the centroids of the areas of workplaces (or departments) that are exchanged. The distance between any two workplaces is represented by the orthogonal distance between the centroids. In the example given, which is based on a pairwise exchange, the difference is 22 % in favour of the modified algorithm.

Keywords: algorithm modification; CRAFT method; layout optimisation; pair-wise exchanges; production layout

1 INTRODUCTION

One of the prerequisites for companies to achieve global competitiveness is the optimal spatial arrangement (layout) of workplaces. The correct and optimal arrangement of workplaces in the production system primarily affects the flow of work items, as well as the flow of information and energy. We want to reduce the costs of internal logistics, i.e. the variable costs of transporting materials between workplaces, as much as possible through a clever arrangement of workplaces. The method of layout planning is largely determined by the type of production; we distinguish between flow line (continuous), intermittent (batch, job shop) and project (individual) production. The flow of the production process and the quantities of material moving through the process are fundamental, so how we arrange the different workplaces in the workshops (departments) is extremely important. We can consider quantitative criteria for the layout, determined by measurable quantities (e.g. transport costs), or qualitative criteria if we cannot determine a measurable material flow, customer flow, etc. between the workplaces and judge which workplaces should be close to or far away from others.

The problem of designing the layout of workplaces is generally the placement of n workplaces (or technological systems) at n or more possible locations, whereby the target function must be fulfilled or the optimum solution found. This theoretically results in $n!$ layout variants, but due to the large size it is not possible to calculate them all [1].

In the following, we restrict ourselves to intermittent production, which comprises a variety of products in moderate quantities. The methods of layout planning are divided into construction methods (opening; we design the initial layout), improvement methods (we try to improve the initial layout) and combined methods (using the two previously mentioned methods). The available analytical (exact) layout planning methods are useful for a layout of max. 8 jobs and are useless for a larger number [2]. In practise, mainly heuristic methods are used due to the complexity of the problem. These methods do not provide optimal, but only sub-optimal layouts that are satisfactory for practical use.

The goals of an optimised workplace layout are:

- shorter transport routes,
- realisation of production in the required quantity, quality and on the desired deadlines,
- shorter throughput times for work orders,
- improved material flow,
- small stocks of unfinished products,
- more safety in the workplace,
- better efficiency of the production system,
- better control of the workplace,
- better communication between workers,
- better utilisation of space,
- better production flexibility,
- lower production costs,
- elimination of bottlenecks, etc.

The criterion for evaluating the placement of workplaces is the variable material transport costs (C_{tr}) between the workplaces, which are determined by Eq. (1) [3]:

$$C_{tr} = \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} D_{ij} F_{ij}, \tag{1}$$

where: n – number of workplaces in the material flow system, C_{ij} – the cost per unit distance for the transport between workplaces i and j, D_{ij} – the distance between the workplaces i and j, F_{ij} – the material flow between the workplaces i and j.

2 DESIGNING OPTIMAL LAYOUT

The initial layout of workplaces can be determined in different ways:

- using one of the construction methods (e.g. Schmigalla triangle method, ALDEP, CORELAP),
- on the basis of the real, existing layout (when reconstructing systems),
- randomly generated.

The optimal layout is determined by improving the initial solution until a satisfactory, sub-optimal layout of the workplaces is achieved. The use of computer programmes has facilitated and accelerated the search for optimal solutions, but a simple, perfect method has not yet been found. Layout improvement programmes carry out workplace relocations in order to reduce transport costs. The best-known programme is CRAFT (Computerised Relative Allocation of Facilities Technique) [4]. This is a classic method in which all possible pairs of workplaces or all triples are exchanged. The process ends when no exchanges bring additional gains, taking into account the target criterion (iterative sub-optimisation).

More recent publications also confirm the relevance of the problem of layout optimisation. Evolutionary optimisation methods are becoming increasingly important. Here are some brief descriptions.

Choi et al. [5] conducted a production simulation in the design phase to optimise the factory layout and used reinforcement learning to derive the optimal factory layout. The reinforcement learning process for optimising the individual components of the layout was implemented in several layers. Lind et al. [6] demonstrated an innovative approach to optimise the production layout that simultaneously considers worker welfare and system performance by using the Non-dominated Sorting Genetic Algorithm II and particle swarm optimisation. Shen et al. used spatial layout optimisation for a different goal – to improve evacuation efficiency in a building [7]. Zhao and Duan [8] described the application of deep reinforcement learning to solve the dual-objective optimisation problem for the layout of workshop facilities. They succeeded in reducing the computational effort. Rodriguez et al. adapted the Systematic Layout Planning methodology with an Industry 4.0 approach [9]. Gue et al. focused on optimising the layout of a workshop for discrete manufacturing based on a digital twin [10].

The CRAFT algorithm also frequently appears in publications that emphasise the practical application as well as the advantages and disadvantages of this method.

Sembiring et al. used the CRAFT algorithm to increase the company's productivity by determining the right plant layout to minimise material handling costs [11]. Prasad et al. used the CRAFT algorithm to design the layout of a production plant within a given area [12]. Amariei et al. present the design stages of a lower-rank production system using heuristic design methods, which are subsequently improved using the CRAFT algorithm [13]. Sadrzadeh presented a genetic algorithm to solve the plant layout problem and proved its efficiency in comparison with another genetic algorithm, the CRAFT algorithm and the entropy-based algorithm [14].

3 CRAFT ALGORITHM

CRAFT, the first computer-aided layout routine, appeared in 1963 [4]. Today, CRAFT is the most frequently used and best described routine for computer-aided layout planning. CRAFT is an improvement algorithm. The inputs to CRAFT include initial layout, flow data, cost per unit distance, total number of departments (workplaces), fixed departments (with locations), area of departments [15]. Fixed departments are usually fixed areas such as stairs, lifts, rest rooms, etc. In the final layout, the transport paths are also fixed areas. The steps of the CRAFT algorithm are:

Step 1. Inputs (as above).

Step 2. Calculate the centroids of the departments in the current layout.

Step 3. Form a distance matrix using the centroids.

Step 4. Calculate the total handling cost of the current layout using the flow, distance and cost data.

Step 5. Find all possible pairwise interchanges of departments based on common border or equal area criteria. Exchange the corresponding centroids for each possibility and calculate the approximate cost.

Step 6. Find the department pair with the lowest handling cost among all possible exchange pairs.

Step 7. Are the costs from the previous step less than the total cost of the present layout? If yes, go to Step 8, if not, go to Step 11.

Step 8. Interchange the selected pair of departments. Label this as the new layout. Calculate the centroids, the distance matrix and the total cost.

Step 9. Is the cost of the new layout less than the cost of the present layout? If yes, go to Step 10, if not, go to Step 11.

Step 10. The new layout is now considered to be the present layout, and its data on centroids, layout matrix and total cost are retained. Go to Step 5.

Step 11. Print the present layout as the final layout. Stop.

Candidates for exchange are characterised by at least one of the following properties: both workplace areas are the same size (but not necessarily the same shape) or the workplace areas have a common border. The exchange is carried out in such a way that the new workplace areas are as far away as possible from the old locations.

3.1 Numerical Example (Presented in [15])

The application of the CRAFT algorithm is shown in an example using the data:

- Total number of departments (n): 5
- Total number of interchangeable departments: 5
- Initial layout is shown in Fig. 1.

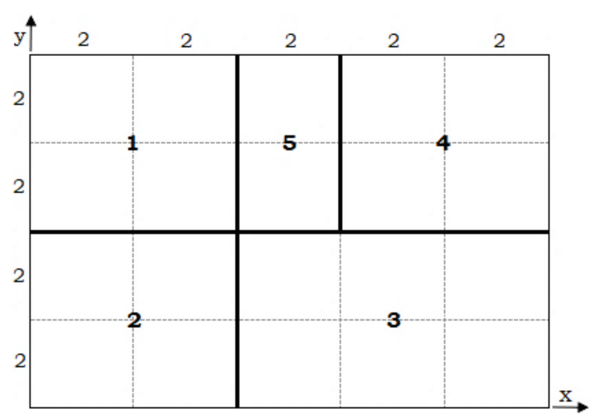

Figure 1 Initial layout for the numerical example

Area of departments 1 to 5: 16, 16, 24, 16, 8 (sq. units).

Cost data per unit distance from department i to department j:

$C_{ij} = 1$ ($i = 1, \ldots, 5$; $j = 1, \ldots, 5$ and $i \neq j$),

$C_{ij} = 0$ (when $i = j$).

The flow matrix $[\boldsymbol{F}_{ij}]$ represents the number of trips in a given period from department i to department j:

From \ To	1	2	3	4	5
1	-	5	2	4	0
2	0	-	2	5	0
3	2	0	-	0	5
4	3	0	1	-	0
5	0	0	2	0	-

Centroids of all the departments in the initial layout:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (8, 6)$, $(X_5, Y_5) = (5, 6)$.

The distance between any two departments is represented by orthogonal distance between the centroids:

$$D_{ij} = \left|X_i - X_j\right| + \left|Y_i - Y_j\right|. \tag{2}$$

The distance matrix $[\boldsymbol{D}_{ij}]$:

From \ To	1	2	3	4	5
1	-	4	9	6	3
2	4	-	5	10	7
3	9	5	-	5	6
4	6	10	5	-	3
5	3	7	6	3	-

Total transport cost matrix $[\boldsymbol{TC}_{ij}]$:

From \ To	1	2	3	4	5
1	-	20	18	24	0
2	0	-	10	50	0
3	18	0	-	0	30
4	18	0	5	-	0
5	0	0	12	0	-

Total (present) transport cost (C_{tr}) = 205.

Pairwise interchanges are considered. For the present problem, eight interchanges are possible at this stage: 1-2, 1-5, 2-3, 3-4, 3-5, 4-5 (on a common border); 1-4, 2-4 (on equal area).

<u>Interchange between 1 and 2:</u>

New centroids:

$(X_1, Y_1) = (2, 2)$, $(X_2, Y_2) = (2, 6)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (8, 6)$, $(X_5, Y_5) = (5, 6)$.

The distance matrix $[\boldsymbol{d}_{ij}]$:

From \ To	1	2	3	4	5
1	-	4	5	10	7
2	4	-	9	6	3
3	5	9	-	5	6
4	10	6	5	-	3
5	7	3	6	3	-

Total transport cost (C_{tr}) = 205.

We continue in the same way (here without the data on the centroids and the distance matrices):

Interchange between 1 and 4: C_{tr} = 193
Interchange between 1 and 5: C_{tr} = 208
Interchange between 2 and 3: C_{tr} = 197
Interchange between 2 and 4: C_{tr} = 201
Interchange between 3 and 4: C_{tr} = 178
Interchange between 3 and 5: C_{tr} = 183
Interchange between 4 and 5: C_{tr} = **163**

The interchange between 4 and 5 results in a minimum (approximate) cost of 163, which is less than the present layout cost of 205. The new layout after the actual interchange between 4 and 5 is shown in Fig. 2. The centroids and the distance matrix are updated. The centroids are:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$,
$(X_4, Y_4) = (6, 6)$, $(X_5, Y_5) = (9, 6)$.

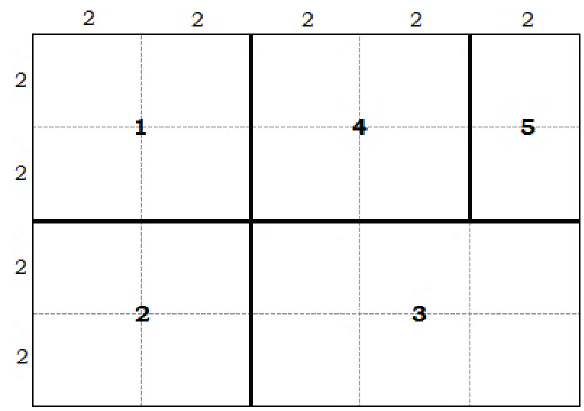

Figure 2 Layout after the 4-5 interchange

Total transport cost (C_{tr}) is 181. This is less than the present layout cost of 205. The new layout replaces the present layout, and we continue with the second iteration.

Six interchanges are possible: 1-2, 1-4, 2-3, 3-4, 3-5 (on a common border) and 2-4 (on equal area). The approximate total cost results for the same sequence of interchanges are: 181, 169, 209, 166, 183 and 181. 166 is the minimum C_{tr} (3-4). This is less than 181. The new layout is shown in Fig. 3.

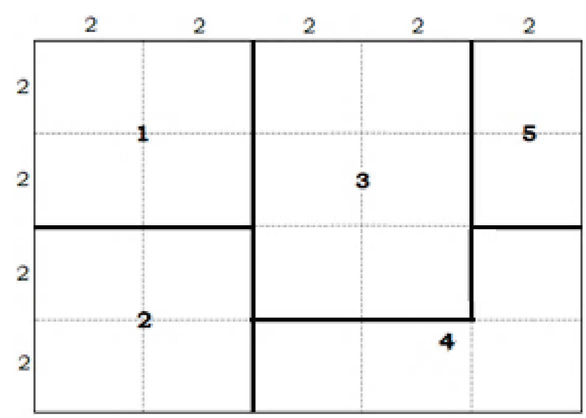

Figure 3 Layout after the approximate calculation in the 2nd iteration

New centroids for exact calculation are:

$(X_1, Y_1) = (2, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (6, 5)$,
$(X_4, Y_4) = (7.5, 1.5)$, $(X_5, Y_5) = (9, 6)$.

New distance matrix [$\boldsymbol{d_{ij}}$]:

From \ To	1	2	3	4	5
1	-	4	5	10	7
2	4	-	7	6	11
3	5	7	-	5	4
4	10	6	5	-	6
5	7	11	4	6	-

Total transport cost (C_{tr}) is 187. This is more than the present layout cost, namely 181. The present layout is the final layout (C_{tr} = 181, which corresponds to a reduction of 12 % compared to the initial 205), see Fig. 4.

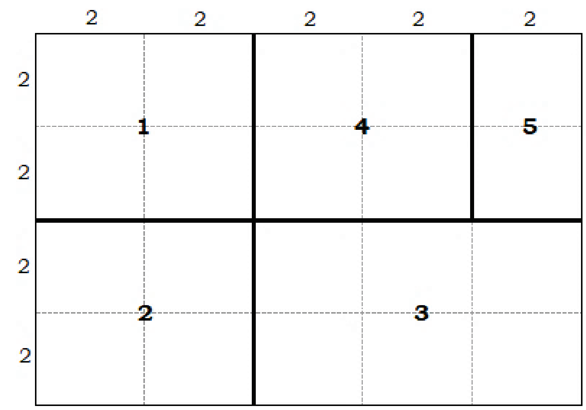

Figure 4 Final layout after the optimisation with the CRAFT algorithm

4 MODIFICATION OF THE ALGORITHM

The calculation of the approximate costs in Step 5 can lead to the optimal solution being lost. When exchanging the locations of departments, differences in distance occur due to different area sizes, so that with the CRAFT method it is always necessary to repeat the calculation with exact values. In our modification of the algorithm, however, we perform an exact calculation on-the-fly so that there are no deviations, and no additional calculation is required. The modifications can be seen in steps 5, 7, 8, 9 and 10:

Step 5. Find all possible pairwise interchanges of departments based on the criterion of common border or equal area. Calculate the exact new centroids and costs for each possibility.

Step 7. Are the costs from the previous step less than the total costs of the present layout? If yes, go to Step 8, if not, go to Step 9.

Step 8. Interchange the selected pair of departments. Label this as the present layout. Go to Step 5.

Step 9. Print the present layout as the final layout. Stop.

Step 10 is cancelled. Our algorithm requires about 10 times more computational effort but leads to a better solution.

4.1 Numerical Example (the Same Data as in Section 3.1)

Given initial layout is optimised with the application of the modified CRAFT algorithm to show its usefulness. For the purpose of cost calculation, an interchange between two departments would mean that their new centroids are calculated. For each interchange, the associated distance matrix is calculated. Then, the exact total transport cost is calculated.

The first iteration gives the same exchange decision as the original CRAFT algorithm (see Tab. 1). But the results for other iterations differ significantly.

Table 1 Exchange pairs and exact total transport costs (iteration 1)

Pair	1-2	1-4	1-5	2-3	2-4	3-4	3-5	4-5
C_{tr}	205	193	231	193	201	182	185	**181**

Layout after the iteration 1 (as in section 3.1), C_{tr} = 181, is shown in Fig. 5.

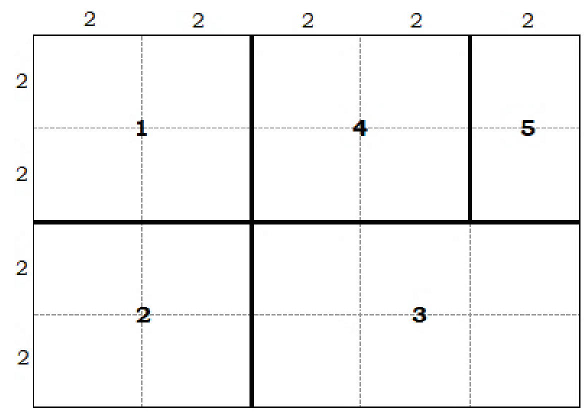

Figure 5 Layout after the 1st iteration

The centroids and the distance matrices are regularly updated. Detailed calculation process is skipped. Six interchanges are possible in the 2nd iteration. All of them are listed in Tab. 2, including the cost results. The interchange pair is 1 and 4 (169 is less than 181).

Table 2 Exchange pairs and exact total transport costs (iteration 2)

Pair	1-2	1-4	2-3	2-4	3-4	3-5
C_{tr}	181	**169**	215	181	187	177

Layout after the iteration 2, C_{tr} = 169, see Fig. 6.

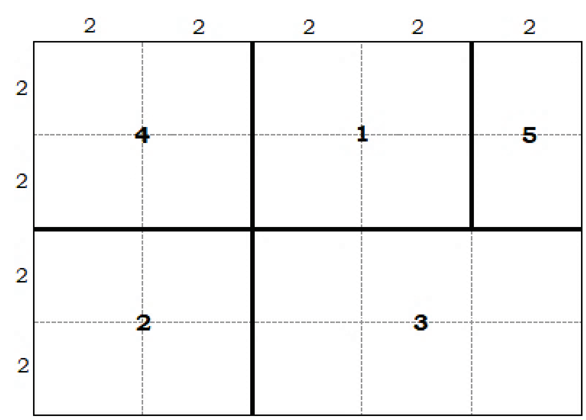

Figure 6 Layout after the 2nd iteration

The centroids are:

$(X_1, Y_1) = (6, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (7, 2)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (9, 6)$.

The centroids and the distance matrices are updated for each interchange. In the third iteration, six interchanges are possible (Tab. 3). The interchange pair is 3 and 5 (165 is less than 169).

Table 3 Exchange pairs and exact total transport costs (iteration 3)

Pair	1-2	1-3	1-5	2-3	2-4	3-5
C_{tr}	169	190	202	221	185	**165**

Layout after the iteration 3, C_{tr} = 165, see Fig. 7.

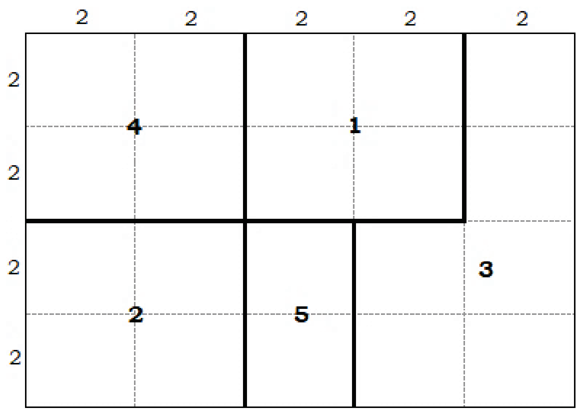

Figure 7 Layout after the 3rd iteration

The centroids are:

$(X_1, Y_1) = (6, 6)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (8.33, 3.33)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (5, 2)$.

Fourth iteration: at this stage, six interchanges are possible (Tab. 4). The interchange pair is 1 and 5 (148 is less than 165).

Table 4 Exchange pairs and exact total transport costs (iteration 4)

Pair	1-2	1-3	1-4	1-5	2-4	2-5
C_{tr}	170	205	177	**148**	175	189

Layout after the iteration 4, C_{tr} = 148, see Fig. 8.

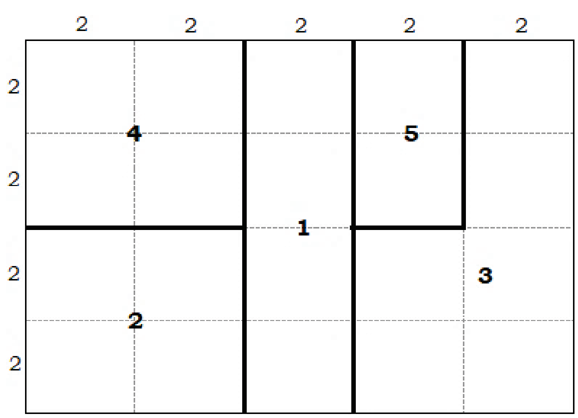

Figure 8 Layout after the 4th iteration (final layout)

The centroids are:

$(X_1, Y_1) = (5, 4)$, $(X_2, Y_2) = (2, 2)$, $(X_3, Y_3) = (8.33, 3.33)$, $(X_4, Y_4) = (2, 6)$, $(X_5, Y_5) = (7, 6)$.

In the fifth iteration five possible interchanges give worse results (see Tab. 5).

Table 5 Exchange pairs and exact total transport costs (iteration 5)

Pair	1-2	1-3	1-4	2-4	3-5
C_{tr}	154	180	163	150	157

The cost of the best layout (150) is not less than the cost of the last layout (148).

The last layout is the final layout. The total transport cost is 148 (28 % less than the initial 205). Department 3 was given a non-rectangular shape.

5 DISCUSSION

The CRAFT algorithm and our modified algorithm are heuristic programmes. They usually provide different solutions to a problem if different initial layouts are available. The literature [16] recommends using no less than three initial layouts as starting procedures. Neither algorithm guarantees an optimal solution. In practise, the limit for layout optimisation has been set at 50 workplaces or departments.

We can interchange workplaces of different sizes, which can lead to very irregular shapes of workstations that may be unusable in practise. Using area centroids to measure distances between workstations is not always realistic (especially for non-rectangular shapes).

To improve the CRAFT algorithm for layout optimisation, several additional improvements can be explored. Incorporating modern heuristic or metaheuristic methods, such as genetic algorithms or particle swarm optimisation, could improve its ability to find near-optimal solutions for complex plant layouts. Adding machine learning techniques could also enable adaptive decision-making based on historical data and contextual factors and further optimise results. Improving the algorithm's ability to handle dynamic and multi-criteria problems could make it even more versatile.

In the given benchmark example [15], the CRAFT algorithm yielded a saving of 12 % in transport costs, while our modified algorithm yielded a saving of 28 % (the value 181 was reduced by a further 18 % to 148, i.e. the result of the CRAFT algorithm is 22 % worse than with the modified algorithm). Our algorithm never delivers a worse result due to its exact calculation.

6 CONCLUSION

Regardless of the type of production (or provision of services), we have four criteria for evaluating the results: quality, quantity, time and cost. The layout of workplaces (or departments) has a significant impact on these criteria, as it promotes quality improvement, stabilises quantities and time consumption and reduces costs. Therefore, we consider the layout of an organisation as a strategic decision for sustainable operation.

The complexity of today's factories requires the use of advanced computer tools for system analysis and design, such as simulation and optimisation. The latest trends are moving towards digital twins of the factory with 3D visualisation and real-time simulations.

In this article, we have shown an improvement of the CRAFT algorithm used for layout optimisation. We decided to make a simple, conventional improvement to the algorithm. With the presented modification of the algorithm we achieve much better optimisation results than with the basic method, with more intensive calculations (weakness) and exact values (advantage). This is also demonstrated using a practical example.

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7 REFERENCES

[1] Polajnar, A., Buchmeister, B. & Leber, M. (2005). *Production Management*, 2nd ed. Maribor: Faculty of Mechanical Engineering (in Slovenian).

[2] Heizer, J., Render, B. & Munson, C. (2017). *Operations Management*, 12th ed. Boston: Pearson Education.

[3] Buchmeister, B. (2024). *Layout Planning in Manufacturing and Services*. Vienna: DAAAM International Vienna.

[4] Armour, G. C. & Buffa, E. S. (1963). A heuristic algorithm and simulation approach to relative location of facilities. *Management Science*, *9*(2), 294-309. https://doi.org/10.1287/mnsc.9.2.294

[5] Choi, H., Yu, S., Lee, D., Noh, S. D., Ji, S., Kim, H., Yoon, H., Kwon, M. & Han, J. (2024). Optimization of the factory layout and production flow using production-simulation-based reinforcement learning. *Machines*, *12*(6), Paper 390, 22 pages. https://doi.org/10.3390/machines12060390

[6] Lind, A., Elango, V., Hanson, L., Högberg, D., Lämkull, D., Mårtensson, P. & Syberfeldt, A. (2024). Multi-objective optimization of an assembly layout using nature-inspired algorithms and a digital human modeling tool. *IISE Transactions on Occupational Ergonomics & Human Factors*, *12*(3), 175-188. https://doi.org/10.1080/24725838.2024.2362726

[7] Shen, N. Z., Cui, J. W., Peng, M., Xu, H. & Wu Z. Q. (2024). An optimization method of large building space based on evacuation simulation. *International Journal of Simulation Modelling*, *23*(3), 435-446. https://doi.org/10.2507/IJSIMM23-3-691

[8] Zhao, Y. L. & Duan, D. L. (2024). Workshop facility layout optimization based on deep reinforcement learning. *Processes*, *12*(1), Paper 201, 14 pages. https://doi.org/10.3390/pr12010201

[9] Rodriguez, L., Loyo, J. & Silva, U. (2023). Layout evaluation with the Industry 4.0 approach for a manufacturing laboratory. *International Journal of Simulation Modelling*, *22*(3), 551-561. https://doi.org/10.2507/IJSIMM22-4-642

[10] Guo, H. F., Zhu, Y. X., Zhang, Y., Ren, Y. P., Chen, M. S. & Zhang, R. (2021). A digital twin-based layout optimization method for discrete manufacturing workshop. *International Journal of Advanced Manufacturing Technology*, *112*(5-6), 1307-1318. https://doi.org/10.1007/s00170-020-06568-0

[11] Sembiring, A. C., Sitanggang, D., Budiman, I. & Aloina, G. (2019). Redesign layout of production floor facilities using algorithm CRAFT. *Proceedings of the 1st International Conference on Industrial and Manufacturing Engineering, Vol. 505*, Paper 012016, 6 pages, Medan, Indonesia. https://doi.org/10.1088/1757-899X/505/1/012016

[12] Prasad, N. H., Rajyalakshmi, G. & Reddy, A. S. (2014). A typical manufacturing plant layout design using CRAFT algorithm. *Proceedings of the 12th Global Congress on Manufacturing and Management, Vol. 97*, 1808-1814, Vellore, India. https://doi.org/10.1016/j.proeng.2014.12.334

[13] Amariei, O. I., Hamat, C. O. & Coman, L. (2013). Designing a lower rank production system. *Proceedings of the 2nd International Conference on Social Science and Education, Vol. 46*, 608-613, Hong Kong, China.

[14] Sadrzadeh, A. (2012). A genetic algorithm with the heuristic procedure to solve the multi-line layout problem. *Computers & Industrial Engineering*, *62*(4), 1055-1064. https://doi.org/10.1016/j.cie.2011.12.033

[15] Panneerselvam, R. (2012). *Production and Operations Management*, 3rd ed. New Delhi: PHI Learning Private Limited.

[16] Tompkins, J. A. & White, J. A. (1984). *Facilities Planning*. New York: John Wiley & Sons.

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A MCDA Based Model for Assessing Digital Maturity in Manufacturing SMEs

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Abstract: This paper presents the findings of research focused on the development of a comprehensive model for assessing the digital maturity of small and medium-sized manufacturing enterprises (SMEs) using multi-criteria decision analysis (MCDA). A systematic review of the literature was conducted to analyse the current state of digital maturity assessment models and evaluate their applicability to the SME sector. The proposed model covers critical digital dimensions relevant to SMEs, including the extent of adoption of digital technologies, the existence of supporting policies and strategies, and the integration of digital technologies into business processes. The developed model enables SMEs to benchmark their current digital maturity level with the desired goals, thus facilitating the formulation of actionable and customized digital transformation strategies. The model was validated through case studies in real production environments to ensure its practical relevance and applicability.

Keywords: Digital Maturity Model; digital transformation; MCDM; SME; strategy

1 INTRODUCTION

The activity of manufacturing companies in today's dynamic market is extremely demanding and challenging. Due to the new conditions created by the pandemic and energy crises of the past, business processes must be adapted to ensure that products are produced faster, with higher quality, at lower costs and in a unique way to maintain or achieve competitiveness. Business processes need to adapt quickly and work as much and as fast as possible towards digital transformation [1]. Digital transformation is a key process in modern companies, enabling them to use new technologies to improve business processes, increase efficiency and drive innovation [2]. In the age of digitalization, assessing a company's readiness for digital transformation is crucial to ensure a successful transition to digital operations [3].

2 DIGITAL TRANSFORMATION

The digitalization and digital transformation (DT) of companies are key processes for the further development of the economy and society and must therefore be approached strategically and comprehensively [2, 4].

2.1 Basic Concepts

The digital transformation and the resulting innovations are changing organizations, institutions and society in a general sense [1]. Understanding the conceptual differences between digitization, digitalization, and digital transformation is crucial for reaching the industrial level of Industry 4.0. Digitization refers to the process of converting physical, analogue objects or properties into a digital format. This includes the conversion of physical documents, audio recordings, images and other materials into binary data that computers can process [5]. Digitalization involves the use of digitized data to improve business processes. This includes automating and optimizing existing processes via digital platforms to become more efficient and productive [6].

Digital transformation is a broader concept that encompasses a fundamental change in the way a company operates through the use of digital technologies. It includes not only the optimization of existing processes, but also the creation of new business models and strategies enabled by digital technologies [7]. In this process, technologies such as big data, artificial intelligence (AI), the Internet of Things (IoT) and cloud computing are used to optimize business processes, improve the customer experience and create new business models [8].

Although these terms are very similar, it is important to understand the characteristics of each term and their proper application in the era of digitalization. Wen et al. confirmed that manufacturing companies with greater sustainability are more adaptable to DT and tend to implement differentiated competitive strategies. Therefore, they concluded that the impact of innovation promotion is greater for firms with higher sustainability [9].

2.2 Investigation of Existing Digital Maturity Models

Digital maturity models are tools or frameworks that assess an organization's internal readiness for digital transformation. Their aim is to provide a deeper insight into the ability of organizations to implement digital technologies and adapt to digital changes in business operations. These models analyse several dimensions, such as organizational culture, strategic capabilities, level of digital skills, technological infrastructure and innovation capability. They are constantly evolving and adapted to specific industries and other characteristics, including industry specific requirements, the size of the organization and the level of development of individual companies.

As there were no clearly defined models for assessing digital maturity, Rossmann's study focuses on defining a concept for building a digital maturity model and the corresponding measurement framework. The results of his study show that the digital maturity framework consists of eight dimensions and 32 factors covering the areas of strategy, leadership, business model, operating model, people, culture, governance and technology. Each dimension includes specific elements that can be assessed based on their maturity level [10]. His work provides a clear theoretical contribution to the conceptualization and operationalization of the framework and extends previous research. Numerous other studies on different existing models have led to the creation of a variety of new variants of digital maturity models because they have identified shortcomings in the existing models [11, 12]. Kruljac and Knežević, analysing twenty-one digital maturity models (out of more than 150 available in the literature), conclude that the analysed models can only serve as analytical tools for assessing digital maturity based on their own criteria. The reason for this is the lack of empirical research on all key elements of the models as well as their limitation to commercial and non-academic application [13]. An analysis of the popular and commonly used models by IMPULS, PwC and Uni-Warwick revealed that they are only partially applicable to SMEs due to a lack of specific relevant categories and practical guidelines that need to be clearly defined and understandable. This allows users to accurately determine the current digital maturity level and areas for improvement [14]. When examining existing maturity models, it was found that none of the existing maturity models for digital transformation fully meet all defined criteria, such as a detailed description of model components, and their applicability across all industries is highly questionable [15]. In their analysis of the adaptation of Industry 4.0 DMM models for manufacturing and logistics companies in SMEs, the authors concluded that there is still considerable room for further research on topics such as digitized production and that the specific requirements of SMEs in the context of developing countries need to be taken into account to enable a more successful adoption of Industry 4.0 [16]. The comparison of existing models conducted in the study provides valuable insights into the current business environment and model requirements and enables the development of new approaches [6]. Future research could focus on analysing the differences in the application of digital maturity models in different industries or investigating the impact of cultural, regulatory and economic factors on the adoption and adaptation of these models in different countries and regions. Very often SMEs have limited resources for business development and improvement to maintain or increase their competitiveness in the market. Therefore, it is important to make appropriate strategic decisions on how to use the limited resources to achieve the best results in improving business processes. Digital transformation indices and digital maturity assessment models provide companies with important guidelines for navigating through digital transformation. The digital maturity model is a useful tool in the company's digitalization process to effectively assess the current state of digitalization and identify key areas for the development of a digitalization strategy. There are numerous examples in the literature that confirm the applicability and necessity of using these tools. Verhoef et al. state that SMEs using digital maturity tools can more easily develop sustainable strategies, reduce operating costs and increase productivity [17]. Westerman & Bonnet emphasize the importance of applying digital maturity models, especially in organizations with limited resources, i.e. SMEs. They find that SMEs using digital assessment models achieve faster results and increase resilience to market changes [3].

The literature review has provided the necessary information and knowledge required for a complete understanding of the specifics of the digital transformation process and its application in different environments. Since there are many models developed for different industries and different applications, it is important to find and select the most appropriate model that can make the greatest contribution on the path to digitalization in an organization.

3 DEVELOPMENT OF A DIGITAL MATURITY ASSESSMENT MODEL FOR SMEs

Most available digital maturity assessment models are predefined for specific industries, company sizes, geographic locations and similar factors. In general, these models are locked to the end user and do not offer the possibility to change the process of digital maturity assessment, such as prioritization and applicability of certain factors in the successful implementation of digital transformation. According to the latest analyses of the achieved industrial level of Industry 4.0, which is often equated with the level of digital maturity, digital maturity in the region is still in its infancy. Apsolon has determined the Croatian Digital Index (HDI), which analyses the readiness of the Croatian economy to face the challenges of extremely rapid growth and the development of new digital technologies by analysing data from 273 Croatian companies [18]. The state of digitalization of the Croatian economy in 2021 was assessed with an average score of 2.59 on the scale of 1 to 5, which is a slight increase compared to 2020, when the score was 2.52. The average score for the digital readiness of companies for digital transformation in 2021 is 3.26. Although the proportion of large companies in this survey is much lower than that of medium-sized companies, it can be assumed that the result for medium-sized and small companies would be significantly lower, namely below the score of 3.0, considering that the awareness, approach and implementation of digital transformation is much more pronounced in large companies. Mladineo and colleagues have continuously analysed the digital maturity of manufacturing companies in the Republic of Croatia over the last decade [19]. The average overall digital maturity score for 2022 is 2.45, while it was 2.15 for 2015. The analysis shows a very low level and very slow progress over the seven years observed. It is therefore clear that there is still a lot of room for improvement and acceleration of digital transformation in Croatia. For a successful digital transformation, companies need to define a precise strategy and guidelines for effectively managing the process. The digital maturity model is a critical success factor as it enables organizations to assess their current state and create roadmaps aligned with their goals [20]. It is impossible to choose the optimal existing model, which is usually developed for a specific industry, environment or organization. The more detailed it is defined, the greater the possibilities for significant deviations in calculating the realistic assessment of the current state and, consequently, in determining the priority activities for improvement. Another major problem is the organization's motivation for digital transformation. Since the level of Industry 4.0 in the Republic of Croatia is 2.45 and reaching the desired level of 4.0 requires a lot of effort and time, the question arises as to how to reduce frustration along the way and increase motivation. One of the tried and tested ways is to make improvements in small but sustainable steps with realistically achievable intermediate goals. A user-customizable solution such as a digital maturity assessment model with the ability to influence the importance of specific areas and priorities of each organization can significantly support the successful journey of digital transformation. For this reason, the development of such a model, applicable in SMEs, was undertaken.

3.1 Definition of Maturity Model

Before the final definition of the model with the corresponding structure was established, the objectives or guidelines for the creation of the model were determined, which must be adapted considering the current state of digital maturity of manufacturing SMEs in our environment. The number of dimensions, the number of digital maturity levels and the number and content of digital transformation elements to be assessed should allow the user to assess the digital maturity level using the model in up to 90 minutes. Due to the differences and specificities between SMEs, it must be ensured that users have the opportunity to influence the determination of the importance of the individual elements of digital transformation.

The first step in defining the basic model is to determine the basic structure of the model itself, i.e., defining the dimensions with the corresponding basic elements and determining the method for validating the importance of the dimensions as well as defining and selecting the number of maturity levels. The conclusions from the presented literature review [8, 10, 11, 15, 16], the current maturity level in SMEs in Croatia [18, 19] and the authors' several years of personal experience in this field led to the selection of the six dimensions and the four levels of digital maturity. The digital dimensions and four levels of digital maturity with brief descriptions are presented in Tab. 1 and Tab. 2.

Table 1 Dimensions of digital transformation in the model

	Dimensions of digital transformation
1	Strategy
2	Technology
3	People and Expertise
4	Operability
5	Products / Processes
6	Organization

The basic elements of digital transformation are the result of a combination of research findings from the available literature and defined models by the following authors: Rossman [10], Schumacher et al. [8], Lichtblau et al. [21], and Ustundag et al. [22].

Certain elements of the mentioned models were revised based on the authors' many years of personal experience in collaboration with competent industry experts with fundamental knowledge of digital transformation.

Initially, 86 elements were defined, which were reduced to 66 elements in 6 dimensions after consultations and adjustments. The number of elements in each dimension varies and ranges from five in the *Products/Processes* dimension to fifteen in the *Technology* dimension, which is also the most important and influential in the entire process of digital transformation.

Table 2 Description of Defined Levels of Digital Maturity

Digital Maturity Stage	Description of the Digital Maturity
1 - Initial Stage	At this level, the company has little or no strategy for digital transformation. Activities are sporadic and not aligned with the company's goals.
2 - Developing Maturity	The beginning of the development of basic digital initiatives, pilot projects and a low level of digital skills among employees.
3 - Defined Maturity	A clear digital strategy is defined, initial integration of digital and business processes begins and processes for digital capability development are established.
4 - Managed Maturity	Digital strategies and technologies are fully integrated into business processes. The company uses data and technology to optimize business efficiency, with a high degree of technology integration, intensive use of analytics and data for decision-making and a digital infrastructure that effectively supports business processes.

Based on the analysis of the presented literature and the exchange of opinions with competent experts from academia and practice in the field of multi-criteria decision making (MCDM) and considering the objectives set for the model, the AHP method — Analytical Hierarchical Process — was chosen to determine the importance of each dimension. The AHP method proposed by Saaty is one of the most popular decision-making methods for solving complex problems, as it includes both subjective and objective evaluation measures. Based on pairwise comparisons, weighting coefficients are calculated by finding the dominant right eigenvector (EV) of the positive reciprocal decision matrix [23]. Pairwise comparisons are also used to determine the relative importance of the alternatives for each criterion [69]. In this way, the user can more realistically and objectively determine the importance weights for each dimension and the corresponding elements of each dimension depending on the strategy and the current state of their organization.

The rating scale for determining the current state of each element of the digital transformation dimension is defined as follows from zero (0) to four (4):
0 – not applicable
1 – completely negative statement
2 – predominantly negative statement
3 – predominantly positive statement
4 – completely positive statement

The basic model was defined using the MS Office package Excel. This complied with the guidelines for the use of readily available software solutions and at the same time allowed a certain degree of autonomy in determining the weighting of the importance of the individual dimensions.

3.2 Digital Maturity Assessment Process Using the DMM Model

It is important to note that the application of the model requires a competent group of experts within the organization who are familiar with the basic concepts, principles, technologies and rules of digital transformation. The group should have a comprehensive understanding of all processes in all areas of business operations, including strategy setting, operational execution, monitoring and reporting on business activities. The size of the group depends on the size and organization of the business processes in each individual company. The process of using the model is illustrated in Fig. 1. The first step in entering data into the digital maturity assessment model is to determine the weighting of each dimension in the model. The chosen method of multi-criteria decision making, AHP, ensures a quick, understandable and objective determination of the weightings for each dimension. This form of applying the open type method was chosen for the sake of simplicity and for a better understanding of how the method works. This form of applying the AHP method in previous studies in collaboration with expert groups from the business community was very well received for these reasons [24].

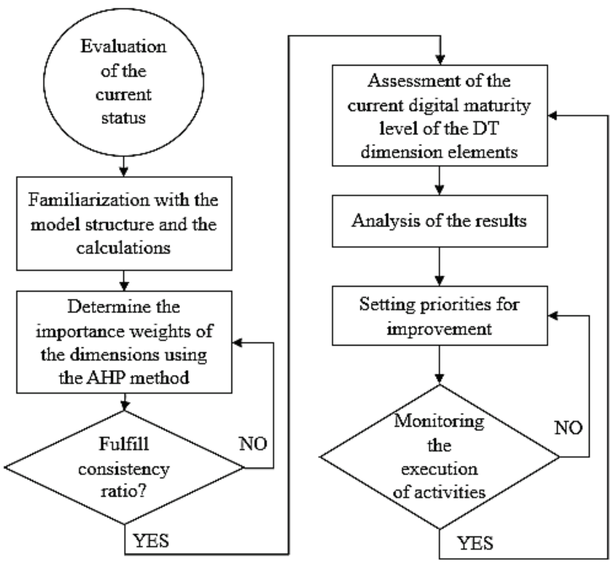

Figure 1 Process of Using the Digital Maturity Assessment Model

After determining the weighting values of the dimensions, the next step is to rate the digital maturity level of each element by selecting a corresponding rating from 0 to 4 from the drop-down menu.

After selecting the available ratings for each element of the digital transformation, the model generates an individual maturity score for each dimension separately according to the mathematical Eq. (1) by Schumacher and authors [8]. In the mathematical expression, M stands for the maturity level, D for the specific maturity level dimension, E for the elements of the digital transformation, g for the weighting coefficient and n for the number of elements of the digital transformation.

$$M_D = \frac{\sum_{i=1}^{n} M_{DEi} \times g_{DEi}}{\sum_{i=1}^{n} g_{DEi}}. \quad (1)$$

The overall result is displayed in the form of tabular values for each individual dimension, as shown in Tab. 3. For practical use, in addition to the tabular representation, a graphical representation of the results by dimension is provided in the form of a radar chart shown in Fig. 2, and the results by dimension element in the form of a sunburst chart. The overall score for the organization's digital maturity level is defined by the minimum score of all evaluated dimensions. The results achieved for the individual digital dimension elements serve as a basis for strategic decisions and the definition of specific activities for digital transformation projects and programs.

Table 3 Digital Maturity Assessment Results for Digital Transformation

DIMENSIONS	MATURITY	Rank
Strategy	2,07	4
Technology	2,16	3
People and Expertise	1,85	6
Operability	2,22	2
Products / Processes	2,40	1
Organization	1,86	5
Average digital maturity	2,09	
Organizational digital maturity	1,85	

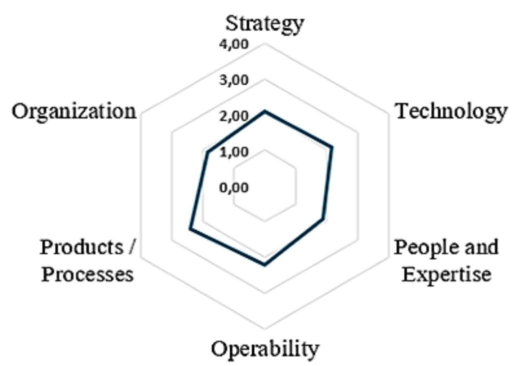

Figure 2 Display of dimensions digital maturity levels by radar chart

4 VALIDATION OF THE MODEL ON A CASE STUDY

The final planned phase in the creation of the new model is its validation using a case study to assess the digital maturity of SMEs in the manufacturing sector. For the validation of the model, three manufacturing companies from the surrounding area were selected, whose experts in specific areas also participated in the development phase of defining individual elements of digital transformation in the digital maturity assessment model. In this way, the competence of users using the model is ensured and qualitative feedback is provided on possible shortcomings or additional user requirements. The selected companies fall into the category of medium-sized enterprises and are active in the manufacturing industry. One company is active in the metal processing industry, another in the glass industry and the third in the production of automotive parts. All companies sell their products on foreign markets, have numerous and high-quality competitors and therefore use the latest manufacturing technologies and are organized according to numerous standards required by the customers or the industries in which they operate.

After receiving the completed digital maturity models from the three manufacturing companies, the individual and collective results of the received models were analysed according to the evaluation procedure shown in Fig. 1. An example of the evaluation results of the weighting values of specific dimensions using the AHP multi-criteria decision method for Company 1 is shown in Fig. 3.

AHP (Analytical Hierarchical Process)
Goal: Determining the Importance of Digital Transformation Dimensions
Note: Fill in only the orange-filled fields

	Digital Transformation Dimensions	AHP	+/-
1	Strategy	32,61%	7,3%
2	Technology	13,76%	7,0%
3	People and Expertise	33,11%	18,3%
4	Operability	8,15%	2,2%
5	Products / Processes	3,81%	2,2%
6	Organization	8,55%	3,6%
		Consistency Result:	8,6%
		Acceptance Criteria: ≤	10,0%

Figure 3 Display of Weight Factor Results for Dimensions in Company 1

The summary of the final scores for individual dimension can be found in Tab. 4. Company 1 has the highest score for the *Products/Processes* dimension (2.4), Company 2 achieves the highest score in the *Strategy* dimension (2.67), while Company 3 excels in the *Organization* dimension (3.3). All companies have low scores in the *Technology* dimension, which could indicate weaker application or outdated technology in terms of digital maturity. The weighting factors for the dimensions indicate that for two companies the *Employees* and *Expertise* dimension is most important, while for the third company the *Strategy* dimension is most important, indicating a focus on planning and long-term strategy. Company 3 has the highest average maturity score (2.55), indicating a better digital maturity level in most dimensions, while Company 1 has the lowest average score (2.09), which could indicate a significant need for investment.

Table 4 Final Results of Digital Maturity Assessment of Dimensions in Companies

Dimension	Company 1	Company 2	Company 3
Strategy	2,07	2,67	2,4
Technology	2,16	1,89	2,0
People and Expertise	1,85	2,54	2,7
Operability	2,22	2,3	2,0
Products / Processes	2,4	1,83	2,8
Organization	1,86	2,29	3,3
Mean	2,09	2,25	2,55
Digital maturity level	1,85	1,83	2,0

The differences between the results of the individual dimensions in the different companies can be interpreted as follows. Low variability between companies was observed in the dimensions of *Technology* and *Operability*, moderate variability in the dimension of *Strategy*, while significant differences in variability were found in the dimensions of *People and expertise* as well as *Products/Processes*. Variability is most pronounced in the *Organization* dimension. This means that although these companies fall into the category of medium-sized manufacturing companies, they have significantly different organizational structures and levels, which can be attributed to their different industries. In terms of consistency between the companies, Company 1 has the highest consistency. Company 2 has the potential to balance the dimensions to reduce variability and ensure development. Company 3 has the most pronounced differences, which can be both an advantage (focusing on key dimensions) and a risk (neglecting weaker dimensions).

Additional feedback, comments and suggestions noted by users of the model during the maturity assessment process were evaluated. There were no significant suggestions or comments that would affect changes to the content concept or mathematical calculations of the dimension and element scores. The comparison of the analysed digital maturity assessment data with the actual state in each company revealed that the model concept correctly measures the differences between the tested manufacturing companies. The model clearly shows differences in certain dimensions and individual elements of digital transformation, regardless of the roughly equal size of the companies and their basic production function. The model developed last year can be gradually extended to new levels by integrating the criteria of Industry 5.0, which focus on human-centred systems. Given the increasing brain drain from the region to developed countries, future research could explore the potential of advanced AI tools such as Chat GPT and Deep Seek to improve the research process and further refine the model to meet Industry 5.0 standards.

5 CONCLUSION

Digital maturity assessment models are an excellent starting point for measuring the current level of digital maturity and assessing the gap to the target level. Considering the numerous peculiarities between the same and different industries, different organizational structures and different specific business processes, there is a need to continuously adapt digital maturity assessment models to different situations. The subject of this paper is the development of a new model for assessing the maturity level of manufacturing SMEs, tailored to the current state of industrial development in Croatia and the specifics of industrial organization and technology in this environment. The defined model was tested in three manufacturing SMEs in the region. The results were thoroughly analysed and the new model for assessing digital maturity in industrial SMEs in Croatia was validated. The analysis results clearly show that the model provides enough consistency and at the same time enough variability to clearly classify the details of the elements of digital transformation. A possible further development of the model is planned in the classification of the necessary activities to improve the elements of digital transformation that are at a low level of digital maturity in order to link them to the business strategy. The additional number of SMEs to be included in further research will provide new insights for the further development of this model and confirm the applicability of the model in SMEs. When the SME's maturity level has progressed towards Industry 4.0, the model is expanded to include an additional set of criteria that are suitable for Industry 5.0.

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6 REFERENCES

[1] Kraus, S., Jones, P., Kailer, N., Weinmann, A., Chaparro-Benegas, N. & Roig-Tierno, N. (2021). Digital transformation: An overview of the current state of the art of research. *SAGE Open, 11*(1), 21582440211047576. https://doi.org/10.1177/21582440211047576

[2] Hess, T. (2022). *Managing the digital transformation: A guide to successful organizational change*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-38424-1

[3] Westerman, G. & Bonnet, D. (2014). *Leading digital*. Harvard Business Review Press. Retrieved from https://www.perlego.com/book/837136/leading-digital-turning-technology-into-business-transformation-pdf

[4] Kalender, Z. & Žilka, M. (2024). A comparative analysis of digital maturity models to determine future steps in the way of digital transformation. *Procedia Computer Science, 232*, 903-912. https://doi.org/10.1016/j.procs.2024.01.090

[5] Vrana, J. & Singh, R. (2021). Digitization, digitalization, and digital transformation. In Meyendorf, N., Ida, N., Singh, R. & Vrana, J. (Eds.), *Handbook of non-destructive evaluation 4.0*, Springer, 717-735. https://doi.org/10.1007/978-3-030-48200-8_39-1

[6] Lang, V. (2021). Digitalization and digital transformation. In Digital fluency (pp. 1-15). Apress. https://doi.org/10.1007/978-1-4842-6774-5_1

[7] Reis, J., Amorim, M., Melão, N., Cohen, Y. & Rodrigues, M. (2020). Digitalization: A literature review and research agenda. In *Industry 4.0 and digital transformation*, Springer, 815-832. https://doi.org/10.1007/978-3-030-43616-2_47

[8] Schumacher, A., Erol, S. & Sihn, W. (2016). A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. *Procedia CIRP, 52*, 161-166. https://doi.org/10.1016/j.procir.2016.07.040

[9] Wen, H. W., Zhong, O. & Lee, C. C. (2022). Digitalization, competition strategy, and corporate innovation: Evidence from Chinese manufacturing listed companies. *International Review of Financial Analysis, 82*, 102166. https://doi.org/10.1016/j.irfa.2022.102166

[10] Rossman, A. (2019). Digital maturity: Conceptualization and measurement model. In *Bridging the internet of people, data, and things: 39th International Conference on Information Systems (ICIS 2018)*, San Francisco, California, USA, vol. 2, 45-58.

[11] De Carolis, A., Macchi, M., Negri, E. & Terzi, S. (2017). A maturity model for assessing the digital readiness of manufacturing companies. In *IFIP International Federation for Information Processing 2017*. Springer International Publishing AG, 125-138. https://doi.org/10.1007/978-3-319-66923-6_2

[12] Haryanti, T., Rakhmawati, N. A. & Subriadi, A. P. (2023). The extended digital maturity model. *Big Data and Cognitive Computing, 7*(1), 17. https://doi.org/10.3390/bdcc7010017

[13] Kruljac, Ž. & Knežević, D. (2019). Modeli digitalne zrelosti poduzeća - objašnjenje, pregled literature i analiza. *Obrazovanje za poduzetništvo - E4E, 9*(2), 72-84. Retrieved from https://hrcak.srce.hr/230577 (in Croatian)

[14] Axmann, B. & Harmoko, H. (2020). Industry 4.0 readiness assessment: Comparison of tools and introduction of a new tool for SME. *Tehnički glasnik, 14*(2), 212-217. https://doi.org/10.31803/tg-20200523195016

[15] Gökalp, E. & Martinez, V. (2021). Digital transformation capability maturity model enabling the assessment of industrial manufacturers. *Computers in Industry, 132*, 103522. https://doi.org/10.1016/j.compind.2021.103522

[16] Elhusseiny, H. & Crispim, J. M. (2023). A review of Industry 4.0 maturity models: Adoption of SMEs in the manufacturing and logistics sectors. *Procedia Computer Science, 219*, 236-243. https://doi.org/10.1016/j.procs.2023.01.286

[17] Verhoef, P. C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Qi Dong, J., Fabian, N., & Haenlein, M. (2021). Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research, 122*, 889-901. https://doi.org/10.1016/j.jbusres.2019.09.022

[18] *Digital transformation in Croatia 2021*. (2025, February 2). Retrieved from https://apsolon.com/publikacije/digitalna-transformacija-u-hrvatskoj-2021/

[19] Mladineo, M., Celent, L., Milković, V. & Veža, I. (2024). Current state analysis of Croatian manufacturing industry with regard to Industry 4.0/5.0. *Machines, 12*(2), 87. https://doi.org/10.3390/machines12020087

[20] Aras, A. & Büyüközkan, G. (2023). Digital transformation journey guidance: A holistic digital maturity model based on a systematic literature review. *Systems, 11*(4), 213. https://doi.org/10.3390/systems11040213

[21] Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A. & Schröter, M. (2015). IMPULS-Industrie 4.0-Readiness. *Impuls-Stiftung des VDMA*, Aachen-Köln. Retrieved from https://impuls-stiftung.de/wp-content/uploads/2022/05/Industrie-4.0-Readiness-english.pdf

[22] Ustundag, A., Cevikcan, E. & Akdil, K. Y. (2018). Industry 4.0: Managing the digital transformation, maturity and readiness model for Industry 4.0 strategy. In *Springer series in advanced manufacturing*, 45-60. https://doi.org/10.1007/978-3-319-57870-5_4

[23] Saaty, T. L. (1980). *The analytic hierarchy process*. McGraw-Hill. https://doi.org/10.21236/ADA214804

[24] Krulčić, E., Pavletić, D., Dobovićek, S. & Žic, S. (2022). Multi-criteria model for the selection of new process equipment in casting manufacturing: A case study. *Tehnički glasnik, 16*(2), 170-177. https://doi.org/10.31803/tg-20220407112829

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Towards Model-based Definition of Digital Product Passports Supporting Sustainable Smart Product Lifecycles

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Abstract: Sustainability has emerged as a key priority across industries, requiring robust mechanisms to enhance transparency and accountability throughout the lifecycle of smart products. The Digital Product Passport (DPP) presents a solution for achieving these goals by aggregating critical product-related data. However, practical implementation encounters significant obstacles, including fragmented data sources and disparate system integrations. This paper presents an approach that uses the Systems Modelling Language (SysML) to overcome these challenges. First, the DPP's essential components are defined and derived from data generated during product development. Implications from the development of the DPP are summarized and contrasted with the potential of a Model-based Systems Engineering (MBSE) approach. The proposed approach establishes traceable relationships between model elements and DPP attributes, enabling seamless data flow. To validate the feasibility and effectiveness, as an example a 3D printer was developed to create an instantiation.

Keywords: Digital Product Passport; Model-based Systems Engineering; Product Development; Product Lifecycle Management; Sustainability

1 INTRODUCTION AND SETTING

The development of smart products has changed significantly in recent decades due to various complexity drivers. On the one hand, products have become more sophisticated and increasingly complex because of the evolution towards smart and networked products. On the other hand, value chains are more complex and more stakeholders have a direct or indirect influence on product creation. Smart products are cyber-physical systems with the ability to connect via the internet that provide various technologies and internet-based services [1, 2]. These properties enable smart products to offer a wide range of possibilities for adding value to the user. Smart products are, therefore, more complex and more challenging to develop. The generation of data and information in the context of development, production and use poses new challenges for data processing and management systems. In addition, new regulations, initiatives and laws require the collection of additional information during the creation and usage of products, for example, to ensure circularity and sustainability. This information must be collected centrally, which can be done using the Digital Product Passport (DPP). At a regulatory level, the European Union (EU) added product creation and evaluation regulations with policy instruments like the Green Deal in 2019. More political initiatives, such as the Clean Industrial Deal, are in preparation. Approaches such as Systems Engineering (SE) can help to solve the problems described in developing smart products. SE is an integrated approach to help develop complex products and support it by processes, methods, information, tools or assemblies to achieve a specific engineering goal [3]. The entire systems lifecycle is in the foreground, which underlines the influence on the circular economy and especially the DPP. Since traditional document-based approaches to systems engineering are often difficult to maintain or evaluate, these challenges can be overcome by using Model-based Systems Engineering (MBSE) in addition to general SE approaches [3]. MBSE serve as an approach with focus on central, digital product representation created systematically and across domains [4, 5]. In this way, the models provide an integrated view of the system, from requirements to the initial concepts in development to detailed planning and production in manufacturing. The models are essential in later use because they can be used as a single source of truth regarding the product, since they are unambiguous, up-to-date and consistent. With MBSE, cycle-oriented product development can be supported [6]. The DPP is currently still in the early phase of its practical introduction. Although some guidelines exist, such as the Digital Battery Passport, large parts of the specific implementation are still unclear [7-11]. In principle, the DPP will apply to a wide range of products in the future and will combine a framework that integrates material information, instructions, and sustainability factors.

The paper presents an approach that collects exemplary system models from the development, production and usage phases and transfers them to a digital product platform which is used as a DPP. To gain an understanding of the DPP, potential data and components of the DPP are collected and clustered. As a set of information, these form a potential framework for a complete DPP. The following models are created and structured in a standardized language to establish traceability. Finally, an industrial implementation is presented that schematically describes the development of a 3D printer as a smart product. The complexity in the development is handled by using an MBSE approach. By linking system-relevant requirements in the development at an early stage, the course is set for further use and intensification. Therefore, the following research questions are answered:

- Which possible data sets can be mapped in the DPP and lead to implications for applied approaches?
- How can an MBSE approach address and resolve these implications at an early stage?

2 EXPLORING DIGITAL PRODUCT PASSPORT

2.1 Defining Digital Product Passport

In a systematic search, thirteen sources were found and examined that provide a basis for DPP, including the EU-funded CIRPASS projects, which developed roadmaps for DPP prototypes in the fields of electronics, batteries and textiles (see Fig. 1). The DPP is defined as a dataset containing product components, materials, chemical substances, reparability details, spare parts availability and disposal information [12, 13]. The DPP evaluates product design performance regarding reusability and tracks product lifecycle, including origin and event history. It records environmental impacts, identifies materials and resources, and provides operational data. Initially based on the Digital Battery Passport, DPP categories include value and supply chain, sustainability and circular economy, diagnostics, maintenance, and performance, and product information [11, 14]. There may be an overlap between categories [15]. The DPP mainly but not only focuses on resource-intensive and complex products [16], providing detailed sustainability information throughout all lifecycle phases from development to disposal or reuse and identifying areas for resource conservation [12, 17, 18]. The introduction of passports that provide detailed information on materials and components is intended to make sustainability opportunities visible throughout the entire lifecycle [19]. This increased transparency ensures consumer awareness of sustainability and thus influences consumer behavior. In this way, sustainable consumption decisions can be increasingly made [10]. At the same time, the DPP acts as an indicator of environmental protection, showing which steps or interventions can be carried out in the product lifecycle to protect resources [19]. Integrating sustainability aspects and taking a comprehensive view of all lifecycle phases is consequently considered a climate-friendly instrument that contributes to achieving an efficient and resource-saving economy [20].

To make informed decisions within a circular value chain, access to all relevant data must be as comprehensive as possible [14]. Therefore, manufacturers, users, and all other parties involved throughout the product lifecycle are included [21]. The DPP promotes the exchange between these different actors, who can be summarized under the term stakeholders. Stakeholders can be divided into two groups: those directly associated with the product (manufacturer, maintenance and/or service provider, end user, etc.) and stakeholders in product regulation (governments or authorities) [13]. Circular value creation is therefore based on the principle of providing all relevant stakeholders with the necessary information in a timely and transparent manner. When implementing the circular economy through the DPP, the concepts of the 9R strategies are of central importance. In particular, the strategies of reconfiguration, repair, reuse, refurbishment, remanufacturing, and recycling [22-24] are paramount. The DPP should support all these processes by providing targeted information on possible repair measures, reuse options or recycling procedures.

Table 1 Suggested information and categories for digital product passport

Category/Subcategory/Information		Sources
	General product information	[11, 13, 15, 25-31]
	Product-specific information	[11, 13, 25, 28, 29, 31, 32]
	Product services	[11, 13, 14, 25, 30, 31]
	Regulation laws and standards	[11, 13, 25, 26, 28-31]
	Storage procedure (operation)	[28, 32]
	Product data	[13, 25, 30]
	Operating and safety instructions	[11, 13, 15, 25, 28, 31, 32]
	User Feedback	[13, 25, 30, 32]
	Components, materials and hazardous goods	[11, 13, 15, 25-32]
	Manufacturing and production information	[11, 14, 15, 25, 27-29, 32]
	Storage procedure	[11, 15]
	Transportation procedure	[11, 15]
Value chain & supply chain	Information on the supply chain	[11, 13, 14, 25, 28, 29, 31, 33]
	Other data of the value chain	[14, 15, 29-31]
	Customer data	[11]
	General information on environmental protection, footprint, CO_2 emissions	[11, 13-15, 25, 28, 29, 31-33]
	Detailed data on environmental characteristics and CO_2 emissions	[15]
	Working conditions and social conditions	[11, 28, 29]
	Energy efficiency/consumption during operation	[11, 14, 25, 28, 29, 33]
	Recycling options	[13, 15, 25, 28-30, 32]
	Disassembly options and instructions	[11, 14, 15, 25, 26]
	Disposal options	[11, 13, 15, 25, 27-29, 31, 32]
Product diagnostics & maintenance	Repair options and instructions	[14, 28, 32]
	Usage history and condition information (also durability)	[11, 14, 15, 25, 30, 31]
	Change History	[11, 13, 15, 25, 27, 28, 32]
	Warranty information	[28]
	Maintenance information	[11, 14, 15, 25, 28, 31]
	Information on spare parts	[11, 31]

In this way, a product's lifecycle can be extended, and material waste can be reduced, leading to a more economical use of natural resources. The individual objectives are closely linked and can each be analyzed at different levels of detail. Sub-strategies can be categorized into three levels to align the DPP with circular strategies such as the 9Rs (see Fig. 1). The lowest level, the energetic level, includes strategies that utilize product components for energy or thermal purposes at the end of their lifecycle. The next level divides product components into materialities for use and recovery in other cycles during or after use. The highest strategy level is the functional level. This examines product components according to their function of reusing and recycling product components in the same, similar, or modified functionality. With each higher level, complexity increases, and so do the potential benefits for the circular economy and the reduction of environmental impacts. The DPP thus forms a data hub that various stakeholders can access to increase resource efficiency and transparency along the product lifecycle in the sense of closed loops [34]. Therefore, the objective and integral part of the DPP should include, standardize, and evaluate detailed information on the functional level.

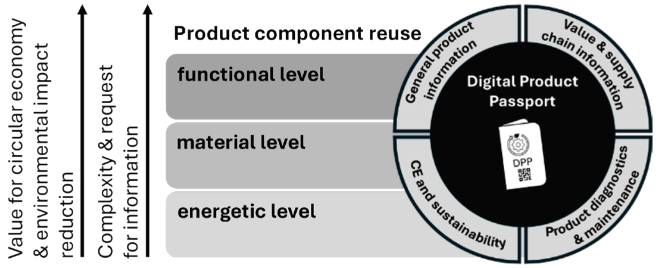

Figure 1 Schematic depiction of the digital product passport with different levels of implementation of sustainability strategies

A detailed DPP can benefit sustainability strategies (and companies that buy parts and components). However, for the respective manufacturers, a detailed product passport represents an increase in effort and, particularly, a risk to trade secrets. It can be expected that each category of company and industry will disclose data on this. However, the question that needs to be clarified is how detailed this information needs to be. Smart products may have unique DPP information requirements. These are currently not being given much consideration, which is why the information requirements for smart products have not been explicitly included in the various tables of content-related components. About legal requirements, for example, the terms of use are considered here as a product parameter, which are needed for the use of software, among other things [35]. This point often affects smart products without being explicitly mentioned here.

2.2 Demands for the DPP

A permanent guarantee of availability, extending beyond the manufacturer's lifespan, must be ensured [8]. Technical and organizational compatibility and interoperability are equally critical, especially where large data volumes are involved [36]. Autonomous data exchange is helpful [36], and legal frameworks can support automated information sharing [8]. With limited resources, companies can opt for DPP-as-a-Service, accompanied by potential financial support measures [37].

The information integrated into the DPP should be selected to minimize administrative overhead [8] while protecting trade secrets. A thorough analysis of information requirements is imperative [38], as these can differ by industry [27], product complexity, or potential for damage [32]. Even under restricted access, sensitive or confidential product information may be required [39]. Therefore, data authenticity, reliability, and integrity must be guaranteed [8]. It is recommended that DPP data be verifiable using internationally recognized standards [39], and new standards may be introduced to bolster data verification [17]. However, the complexity of the DPP can make uniform standardization more challenging [17]. Data collection may rely on the Internet of Things, cryptographic authentication, artificial intelligence (AI), machine learning, or digital twin technologies [40]. The collected data undergo curation processes, such as de-noising, cleansing, imputation, and linking databases via digital threads, alongside big data analysis [40]. Furthermore, the data transmission interval must be clearly defined [27], and all product information must remain current throughout its lifecycle [40]. The DPP should address existing legislation such as the right to repair, extended producer responsibility, and the General Data Protection Regulation [27]. In addition, creating shared standards for data requirements and data protection is advisable [37], but the DPP's inherent complexity can complicate establishing universal norms [17].

2.3 Implications for a MBSE Approach

Based on the established requirements, implications for an approach from the product development perspective will be transferred. By clustering into potentials (P1-P5), relationships can be established:

P1 Data management, traceability and modeling: Due to the increased complexity caused by smart products and large and complex value chains, an MBSE approach contributes to reducing this complexity by systematically describing systems. A uniform and standardized language meets the distinct call for standardization across all value-added partners and administration in an MBSE environment. For example, SysML ensures uniformity as a system modeling language with components for requirements up to product structures. The transfer into other data formats, such as XML or JSON, and the correlation of this data between languages, enables independent and standardized exchange. A model-based approach ensures uniform modeling languages and the intuitive networking of models, even across different lifecycle phases. The necessity for standardized, unambiguous and versioned identifiers of the models and metadata can be met and even further developed and promoted in an MBSE environment. Interfaces and configuration points are also already part of model-based approaches.

P2 Lifecycle and sustainability: The necessity for central collection, storage and tracking of sustainability-related information distributed over the lifecycle, such as requirements, must already be created and thought through in the development of the products. MBSE offers the possibility of laying the foundation for the requirements of the DPP. By consciously creating requirements for this, products can be compared with established requirements in later phases. Generalized creation for product requirements, which result from the 9R strategies, can also be integrated in the early stages of development via model-based integration. The feedback of usage data (actual data) to the sustainability-related information created in the requirements model is not only possible via the model-based approach but is expressly desired.

P3 Variation and integration: DPP requirements such as the embedding of product variants and their compatibility in a central system model, the development of a digital twin that can interact with the DPP, the consideration of supplier and stakeholder data in the system models and the standardized exchange of information using ontologies and reference models are not only possible via MBSE, but are an integral part of it. The early stages of development are crucial, as they set the course for later seamless integration and the definition of interfaces to the digital twin, for example.

P4 Compliance & Security: Compliance with legal, normative and internal company regulations, which are an integral part of the DPP, can be ensured in MBSE methods, for example, by formally recording them in requirements. Role and data access management can also be represented officially using MBSE.

P5 Automation & Forecasting: The generation of context-related information for later lifecycle phases or sustainability strategies should be part of the DPP. Automated forecasting models or strategy recommendations can be used to achieve this. However, this requires machine-readable and machine-interpretable data. The consistent, versioned and standardized language in MBSE models and the possibility to compare this real-time data in use enable potential for AI applications. The forecast models correlated on the MBSE models with usage data are only possible through the consistent use of the model-based application.

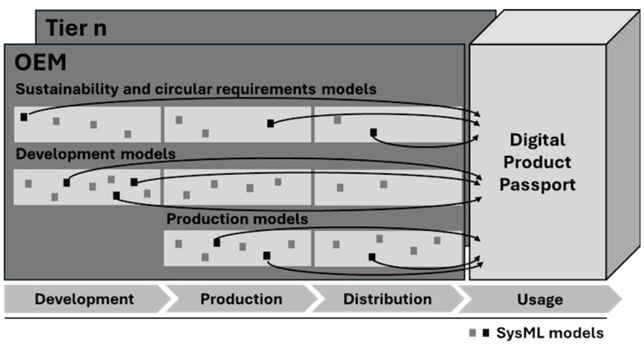

Figure 2 Model-based digital passport creation

Fig. 2 schematically shows how various system(sub-) models from different phases, domains and development stages are extracted into the DPP. The selection of models is adapted to the importance of the objectives already described.

3 DEVELOPING A MODEL-BASED 3D PRINTER DPP

A commercial, consumer-grade and beginner-oriented 3D printer is designed and validated using a model-based development approach to fully handle DPP requirements. Several system models in different product creation phases are created and connected (see Fig. 3).

A general requirements model in which the 9R sustainability strategies, including enhanced strategies like reconfiguration, are defined as overarching goals. Various system models have been developed to handle individual development goals. These include a specific requirements model for the 3D printer with functional, performance and safety requirements, a functional model that divides the printing process into sub-functions such as material supply, heating, print head movement and layer deposition, a product structure in which the individual components (e.g. frames, extruders, sensors) and their interrelationships, a material model that describes the materials used (e.g. plastics, metals) and their properties in terms of durability and recyclability, and a usage data model that collects information about maintenance, usage cycles, wear and tear, and operating environments (e.g. temperature, humidity). These models are linked using unified, standardized language (in this case SysML and JSON). This creates a consistent digital image of the 3D printer, ranging from the initial sustainability requirements (based on the 9R strategies) to the physical components and the actual operating and maintenance data. Implementing a DPP for a complex product such as a 3D printer requires a holistic view of several factors. As early as the development stage, ecological and sustainability-related requirements (e.g., resource conservation, reusability of components) must be incorporated into the general requirements model and later specified in the material and product structure model. Merging the functional model (description of the processes) with the physical model (components) and the material model (material properties) is challenging. Consistent modeling allows for a seamless data flow from the requirements to actual operation.

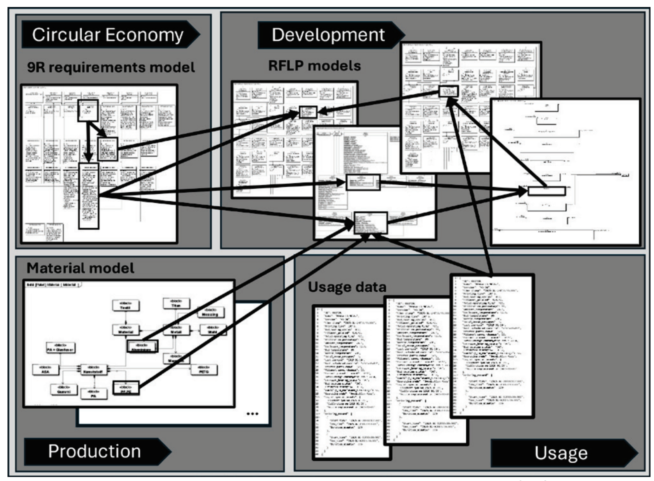

Figure 3 Model-based digital product passport data models of a 3D printer

A 3D printer can be developed or produced in different configurations (e.g. different print volumes, nozzle types). All variants must be mapped in the model and traced later in the DPP. At the same time, data from external partners (suppliers, stakeholders) must be integrated into the system model. Legal provisions and internal guidelines (e.g. regarding data protection or occupational safety) must be formally stored in the requirements. Due to the large number of specifications and standards, this can quickly become confusing. The possibility of using real-time data from the usage data model for AI-supported predictions or maintenance strategies requires that all data is machine-readable and available in standardized formats. MBSE offers a structured approach to overcome the abovementioned challenges. By using SysML or JSON, requirements, function models, product structures, and usage data are recorded in a standardized form. This ensures a clean interface definition and facilitates data exchange between different tools. Each sub-model is linked to the relevant building blocks of other models (e.g., requirement links in SysML). For example, sustainability requirements (9R strategies) can be traced back to the material model and later validated by accurate usage data. MBSE methods make it possible to capture different versions of the 3D printer in a central model. This facilitates the management of product variants and simplifies integration into the DPP. Legal and normative requirements are formally stored in the requirements model. Safety-related aspects (e.g., access to specific assemblies or materials) can be controlled via role and rights concepts. Since all data is available in standardized, versioned formats, automated analysis during the operation of the 3D printer (e.g., for predictive maintenance) is easily possible. The usage data model can provide real-time information, which is evaluated for forecasts and optimization strategies.

4 CONCLUSION

The model-based approach ensures comprehensive traceability and integration of all relevant data throughout the product lifecycle. The potentials P1 to P5 can be met as follows:

- P1: A uniform modeling language and standardized interfaces enable consistent data management with explicit, versioned identifiers.
- P2: The early anchoring of the 9R sustainability strategies in the requirements model and their implementation in the material and usage data model ensure that sustainability aspects can be considered and verified over the entire lifecycle.
- P3: The mapping of different 3D printer variants and the integration of supplier data are facilitated by MBSE. In addition, the model-based system description lays the foundation for a possible connection to a digital twin.
- P4: Formal and versioned requirements allow legal and normative specifications to be mapped, while role concepts can be stored in the model.
- P5: The consistent, standardized database allows the use of AI algorithms for prediction (e.g. maintenance requirements, material consumption) and contributes to automated decision-making.

In summary, the approach presented systematic management and organization of complex multi-domain data over the lifecycle with seamless, standardized and traceable data integration into the DPP. The possible correlation between the development models and the data requirements of the DPP is shown.

Although MBSE already meets many of the requirements of the DPP, the complementary use of a product lifecycle management system (PLM) can contribute to further optimization. Above all, a PLM system enables efficient change and version management across all phases and seamlessly integrates additional processes (e.g. release and supplier workflows) into the overall digital picture. In this way, model-based development can be further professionalized and extended beyond the boundaries of individual departments and companies. However, the details of integrating machine-readable information from modeling into a PLM environment need to be further investigated and refined. The automated extraction of product information relevant to the DPP is also part of future research.

5 REFERENCES

[1] Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. *Harvard Business Review*, 64.

[2] Tomiyama, T., Lutters, E., Stark, R., & Abramovici, M. (2019). Development capabilities for smart products. *CIRP Annals*, 68, 727. https://doi.org/10.1016/j.cirp.2019.05.010

[3] Walden, D. D., Roedler, G. J., Forsberg, K., Hamelin, R. D., & Shortell, T. M. (Eds.). (2015). *Systems engineering handbook: A guide for system life cycle processes and activities* (INCOSE-TP-2003-002-04, 4th Ed.). Wiley.

[4] Friedenthal, S. (2014). *A practical guide to SysML: The systems modeling language* (3rd Ed.). Elsevier Science.

[5] Roodt, D., Nadeem, M., & Vu, L.-T. (2020). Model-based systems engineering for complex rail transport systems – A case study. *Systems Engineering*, 30, 1581. https://doi.org/10.1002/j.2334-5837.2020.00805.x

[6] Werner, M., Potinecke, T., Block, L., & Edel, F. (2023). Nachhaltigkeitsorientierung im Life Cycle Engineering. In *Mit Digitalisierung und Nachhaltigkeit zum klimaneutralen Unternehmen* (p. 239). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-42485-5_14

[7] European Commission. (2019). *Communication from the Commission - The European Green Deal*.

[8] European Commission. (2022). *Proposal for a regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC*.

[9] Bundesministerium für Wirtschaft und Klimaschutz (BMWK). (2024). EU-Mitgliedstaaten machen den Weg frei für nachhaltige Produkte. Möglichst viele Alltagsprodukte sollen zukünftig langlebig, energiesparsam und leicht reparierbar sein. (in German)

[10] Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a digital product passport fit for contributing to a circular economy. *Energies*, 14, 2289. https://doi.org/10.3390/en14082289

[11] Stratmann, L., Hoeborn, G., Pahl, C., & Schuh, G. (2023). Classification of product data for a digital product passport in the manufacturing industry. *Hannover publish-Ing*.

[12] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV). (2024). Was ist ein digitaler Produktpass? (in German)

[13] King, M. R., Timms, P. D., & Mountney, S. (2023). A proposed universal definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, discrete capabilities, stakeholder requirements, and concerns. *Journal of Cleaner Production*, 384, 135538. https://doi.org/10.1016/j.jclepro.2022.135538

[14] Berger, K., Schöggl, J.-P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*, 353, 131492. https://doi.org/10.1016/j.jclepro.2022.131492

[15] Psarommatis, F., & May, G. (2024). Digital product passport: A pathway to circularity and sustainability in modern manufacturing. *Sustainability*, 16, 396. https://doi.org/10.3390/su16010396

[16] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV). (2024). Für welche Produktgruppen eignet sich der digitale Produktpass? (in German)

[17] Nowacki, S., Sisik, G. M., Angelopoulos, C. M. (2023). Digital product passports: Use cases framework and technical architecture using DLT and smart contracts. In *2023 19th International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)* (p. 373). IEEE. https://doi.org/10.1109/DCOSS-IoT58021.2023.00067

[18] European Commission. (2024). *Ecodesign for sustainable products regulation*. The new regulation will improve EU products' circularity, energy performance, and other environmental sustainability aspects.

[19] Munaro, M. R., & Tavares, S. F. (2021). Materials passport's review: Challenges and opportunities toward a circular economy in the building sector. *Built Environment Project and Asset Management*, 11, 767. https://doi.org/10.1108/BEPAM-02-2020-0027

[20] Götz, T., Adisorn, T., & Tholen, L. (2021). Der digitale Produktpass als Politik-Konzept. *Kurzstudie im Rahmen der Umweltpolitischen Digitalagenda des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit (BMU)*. Wuppertal Institut für Klima, Umwelt, Energie. (in German)

[21] Saari, L., Heilal, J., Heikkilä, T., Kääriäinen, J., Pilkkinen, A., & Rantala, T. (2022). Digital product passport promotes sustainable manufacturing. *Oulu*.

[22] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221. https://doi.org/10.1016/j.resconrec.2017.09.005

[23] Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain*.

[24] Juresa, Y., Mollahassani, D., & Goebel, J. C. (2024). Addressing circularity strategies by reconfiguring smart products during their lifecycle. *Technological Forecasting and Social Change*, 18, 452. https://doi.org/10.31803/tg-20240516125344

[25] van Capelleveen, G., Vegter, D., Olthaar, M., & van Hillegersberg, J. (2023). The anatomy of a passport for the circular economy: A conceptual definition, vision, and structured literature review. *Resources, Conservation and Recycling*, 17, 200131. https://doi.org/10.1016/j.rcradv.2023.200131

[26] Gallina, V., Gal, B., Szaller, Á., Bachlechner, D., et al. (2023). Reducing remanufacturing uncertainties with the digital product passport. In *Manufacturing Driving Circular Economy* (p. 60). Springer International Publishing. https://doi.org/10.1007/978-3-031-28839-5_7

[27] Jansen, M., Meisen, T., Plociennik, C., Berg, H., et al. (2023). Stop guessing in the dark: Identified requirements for digital product passport systems. *Systems*, 11, 123. https://doi.org/10.3390/systems11030123

[28] Timms, P. D., & King, M. R. N. (2023). Complexity in the delivery of product passports: A system of systems approach to passport lifecycles. In *2023 18th Annual System of Systems Engineering Conference (SoSe)* (p. 1). IEEE. https://doi.org/10.1109/SoSE59841.2023.10178575

[29] Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., et al. (2023). Data requirements and availabilities for a digital battery passport – A value chain actor perspective. *Cleaner Production Letters*, 4, 1. https://doi.org/10.1016/j.clpl.2023.100032

[30] Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., et al. (2023). Factors of digital product passport adoption to enable circular information flows along the battery value chain. *Procedia CIRP*, 116, 528. https://doi.org/10.1016/j.procir.2023.02.089

[31] Jensen, S. F., Kristensen, J. H., Adamsen, S., Christensen, A., et al. (2023). Digital product passports for a circular economy: Data needs for product life cycle decision-making. *Sustainable Production and Consumption*, 37, 242. https://doi.org/10.1016/j.spc.2023.02.021

[32] Plociennik, C., Pourjafarian, M., Saleh, S., Hagedorn, T., Carmo Precci Lopes, A. do, Vogelgesang, M., Baehr, J., Kellerer, B., Jansen, M., Berg, H., Ruskowski, M., Schebek, L., & Ciroth, A. (2022). Requirements for a digital product passport to boost the circular economy. *Gesellschaft für Informatik*, Bonn.

[33] Voulgaridis, K., Lagkas, T., Karampatzakis, D., Argyriou, V., et al. (2023). Realizing digital product passports with crowdsourcing principles: The case of sustainable smart grids. In *2023 19th International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)* (p. 381). IEEE. https://doi.org/10.1109/DCOSS-IoT58021.2023.00068

[34] Verein Deutscher Ingenieure e.V. (2002). *Recyclingorientierte Produktentwicklung*. Beuth Verlag. (in German)

[35] European Commission. (2022). *Annexes to the Commission proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC*.

[36] Heeß, P., Rockstuhl, J., Körner, M.-F., & Strüker, J. (2024). Enhancing trust in global supply chains: Conceptualizing digital product passports for a low-carbon hydrogen market. *Springer Journal of Industrial Engineering and Management*, 34, 1. https://doi.org/10.1007/s12525-024-00690-7

[37] CIRPASS. (2024). *Making the DPP a success: Recommendations for action*.

[38] Verband der Elektro- und Digitalindustrie e.V. (2022). *Position zum EU Digital Product Passport (DPP)*. (in German)

[39] Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., & Chowdhury, T. (2022). Digital product passport: The ticket to achieving a climate neutral and circular European economy? Wuppertal Institut für Klima, Umwelt, Energie.

[40] Voulgaridis, K., Lagkas, T., Angelopoulos, C. M., Boulogeorgos, A.-A. A., et al. (2024). Digital product passports as enablers of digital circular economy: A framework based on technological perspective. *Journal of Signal Processing Systems*, 85, 699. https://doi.org/10.1007/s11235-024-01104-x

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Integrating Motion Capture Technology into Ergonomics Design: Managerial Implications for Systemic Safety Management

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Abstract: In the era of increasing attention to ergonomic work organization (which also affects employee safety), ways are being sought to improve and detail ergonomic analyses aimed at proposing ways to improve working conditions. One such method may be the use of Mo-Cap technology, which allows for examining the position of employee body segments while performing key activities at work. The findings are at least partially compatible with ergonomic assessment techniques, e.g. REBA, in order to obtain a more accurate analysis resulting from better recognition of work planes. The presented article focuses on recognizing the possibilities of using Mo-Cap in ergonomic analyses on selected examples. The positive aspects of the application were identified (e.g. better recognition of the employee's body position during work) as well as limitations (e.g. lack of possibility to translate the ad-reading into determining the angles of the body segments' position). The results support the use of ergonomic assessment methods. They are also analyzed in relation to the benefits and barriers of using Mo-Cap technology in ergonomic analyses.

Keywords: ergonomics; motion capture; system work safety

1 INTRODUCTION

In companies (especially manufacturing ones), there is an increase in awareness of the appropriate design of workstations and the need to improve the quality of ergonomics of existing ones. With increasing awareness, employers attach increasing importance to the work environment in which their employees spend time and work every day. With the well-being of employees in mind, workstations are increasingly assessed in terms of their functionality and ergonomics. It happens that existing workstations, despite fulfilling their function in relation to the process, do not provide ergonomics, and therefore may cause ailments in employees. In a situation where employers decide to introduce changes to existing workstations in order to improve the comfort of employees' work, we are dealing with so-called corrective ergonomics, which deals with the analysis of existing workstations in terms of their adaptation to the psychophysical capabilities of employees [1, 2]. In order to analyze workstations, ergonomic assessment of workstations is performed. This assessment can be carried out using well-known methods and tools such as REBA, RULA, OWAS, 3DSSP [3] or applications measuring angles, e.g. Navo Smart. Each method has a specific purpose and evaluation principles, and each method has its limitations. These limitations are particularly important in standard assessments - they usually result from a subjective approach to the appropriate determination of risk, e.g. the position of a given body segment or the determination of the frequency of performing a given activity [4]. For this reason, ways are sought to objectify the assessments and provide a more accurate description of the work before starting the ergonomic assessment using the selected method [5].

This article examines the possibilities of using Motion Capture technology (Neuron Perception system with Axis Studio Quick Start Guide software) for ergonomic evaluation of selected production workstations and determines the justification, benefits, and limitations of using this technology in this case. The aim of this work is to assess the potential of Mo-Cap in precise monitoring and analysis of employee movements, which can contribute to improving ergonomic assessment processes and support traditional methods, becoming an integral part of Systemic Safety Management.

2 APPROACHES USED FOR ERGONOMIC ASSESSMENTS IN PRODUCTION WORKSTATIONS

2.1 Selected Methods of Ergonomic Assessment

In ergonomic assessment, various methods are used, usually adapted to the assessed workstation in terms of the employee's position at work or the occurrence of a specific type of load that should be examined. Among them, we can distinguish methods in which data related to the employee's effort is processed, e.g. heart rate monitoring or electromyography [6], but their use is limited due to the need to have appropriate equipment and to perform measurements over a long period. For this reason, methods based on observation are more popular, based on which an assessment is made according to the instructions and the scoring provided in the method. Among the known and frequently used methods, it is possible to distinguish [7-9]:

- methods based on the assessment of the position of body segments while performing specific key activities at workstations, e.g. RULA, REBA, OWAS,
- methods for assessing a given employee's workload, e.g. carrying or lifting; these include: NIOSH Lifting Equation or MAC,
- methods focusing solely on a given body segment, e.g. the work of the wrists and hands (e.g. Strain Index or OCRA),
- questionnaire methods and methods based on the employee's assessment of their ailments on an adopted assessment scale.

In the case of each method, limitations in their use are noted, especially in the area of correct reading of the position of the body segment or determining angles, e.g. rotation or collection of work materials. For this reason, the use of these methods should be performed by an experienced observer and supplemented with additional measurements in order to assess as accurately as possible [10].

2.2 Advanced Technologies in Ergonomic Assessment

In ergonomic assessment, methods that go beyond the standard are increasingly used, in which it is possible to model the workstation by supplementing appropriate parameters. This allows for a more accurate assessment and obtaining a report on the most hazardous activities for the employee during work. An example of such a method is 3DSSPP, where it is possible to model the workstation and precisely determine the parameters necessary for evaluation, e.g. angles [11]. Another example is the modelling of the workstation and ergonomic assessment using the JACK system, in which it is possible to obtain a report on the employee's workload based on the introduction of appropriate parameters related to the employee and the work environment [12]. Elements of machine learning are also increasingly used for ergonomic analysis. This allows for automatic calculation of results based on snapshots or digital video using computer vision and machine learning techniques. The use of such a solution helps to reduce the subjectivity of ergonomic assessments and also allows for the assessment of several workstations at once using an appropriate number of recording devices [13]. An interesting, new direction of development of ergonomic assessments is the use of artificial intelligence elements in this process. Thanks to the automation of assessments, it is possible to quickly diagnose the position of employee body segments and quickly analyze the obtained data, often together with proposals for introducing corrective changes at the workstations. AI also supports the establishment of an employee training strategy in terms of ergonomics and supports the creation of short- and long-term plans in the context of increasing the ergonomic quality of workstations [14,15].

2.3 The Use of Mo-Cap in Ergonomic Assessment

There is a growing interest in the use of Motion Capture in ergonomics. This technology allows for precise recording and then analysis of the position of objects or characters in the real world. This data is then processed into a digital format [16]. There are two models of Mo-Cap technology:

- optical systems operating on the principle of infrared light sent from cameras to markers,
- inertial systems - based on sensors placed on costumes or on the human body.

The sensors are equipped with an accelerometer, magnetometer and gyroscopes, which create an autonomous system without reference points (as in the case of the optical system) [17]. The following benefits of using mo-Cap in ergonomics are noted:

- improving the speed and accuracy of collecting movement data,
- creating conditions very close to real life,
- processing many data simultaneously,
- the possibility of partially translating, the obtained results into standard ergonomic assessment methods [18].

Certainly, the limitation of using Mo-Cap for ergonomic assessments is the availability of hardware and software as well as the lack of appropriate knowledge on how to use them. Another problem may be the lack of possibility to fully transfer the results to the selected ergonomic assessment method.

3 METHOD OF RESEARCH

In the undertaken research, an ergonomic analysis of the selected workstation was conducted. Standard ergonomic methods were used, such as the 3DSSPP method, REBA and RULA based on data obtained from the use of Mo-Cap technology. The Neuron Perception Studio was used. It is a system and software based on Inertial Measurement Units (IMUs) integrating accelerometers, gyroscopes, and magnetometers to track movement in three-dimensional space. In Neuron Perception system are used 17 wireless sensors placed on key body joints to provide real-time motion data transmission via Bluetooth protocol. The Perception Neuron Studio (PNS) was used due to its high flexibility, portability, and resistance to magnetic interference, this system has been widely used in animation, virtual reality, biomechanics, and sports science, proving to be an efficient alternative to optical-based Mo-CAP solutions. PNS offers several advantages for ergonomics, including its cost-effectiveness and user-friendly setup compared to traditional optical systems like OptiTrack. Its high consistency in measuring upper-body kinematics, with CMC values ranging from 0.73 to 0.99, allows for accurate assessments of movement patterns. Additionally, the PNS can capture data across various task complexities and movement speeds, making it suitable for comprehensive ergonomic evaluations in biomechanical research [19].

The first stage of the research was preparing the equipment and reading the instructions for its use. The following research techniques and methods were then used:

1) Direct observation.
2) The use of Motion Capture technology using the Perception Neuron set.
3) Recording of selected activities using cameras.
4) Measurement of forces using a dynamometer (context data for assessment) - FB2K AXIS dynamometer ensuring measurement accuracy of ±0.1% of the range.
5) Analysis of results and comparison with applicable standards and regulations.
6) Biomechanical analyses using the 3DSSPP program and the REBA or RULA methods.

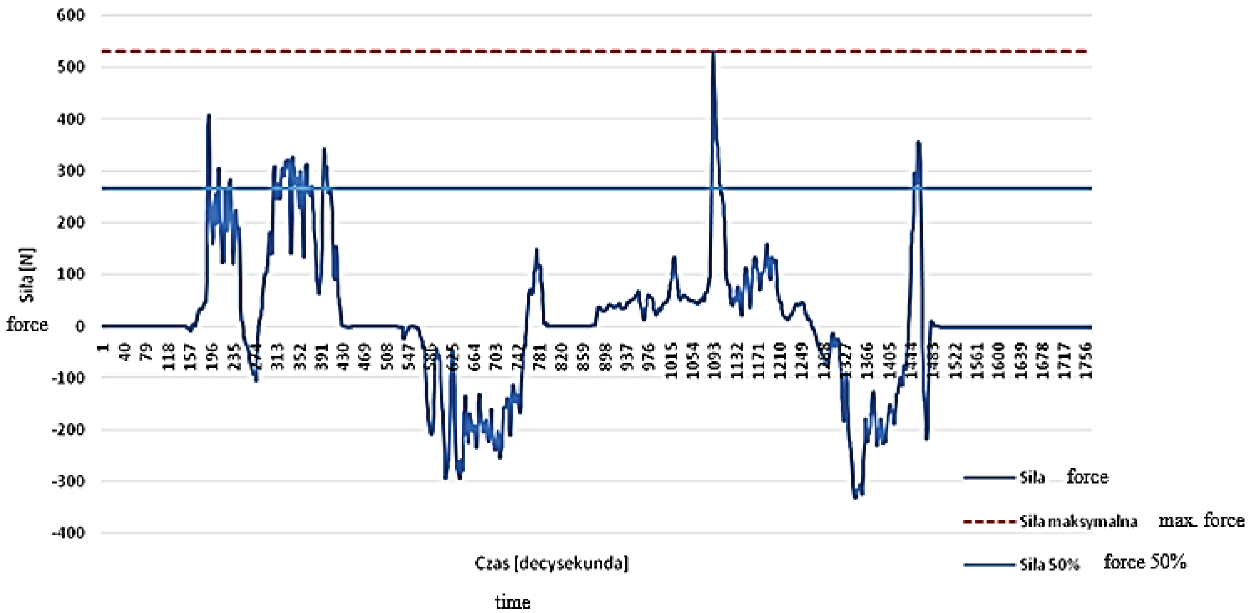
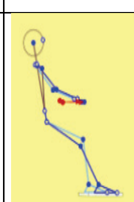
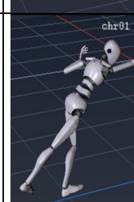
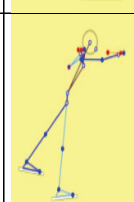
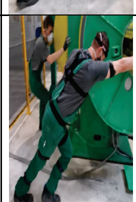
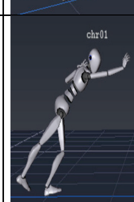
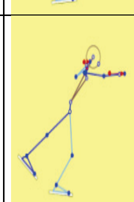
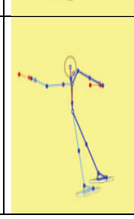


Figure 1 Forces measured at the selected workstation using a dynamometer

The results obtained in the studies were analyzed in terms of the consistency of the data obtained through the Mo-Cap assessment with the standard assessment and the potential of using this technology in ergonomic assessments was determined.

Table 1 Results of selected workstation assessments

Activity	Picture	Mo-Cap	3DSSPP	REBA Score
Pulling reel 1				12 - very high risk
Pushing reel 1				11 - very high risk
Pushing reel 2				12 - very high risk
Pulling reel 2				12- very high risk

Source: own elaboration

4 RESULTS

In order to achieve the aim of this research, i.e. to indicate the potential of using Mo-Cap technology in ergonomic assessments and in systemic management of employee safety, a production workstation with pushing and pulling activities was selected for assessment. Fig. 1 presents the values of forces measured using a dynamometer for contextual indication of the employee's load. Then, four key activities performed by the worker were shown, taking into account the motion capture reading and 3DSSPP and REBA assessment.

Tab. 1 indicates the key activities performed by the employee along with selected assessments.

To show an example of the evaluation result for activity 1 "Pulling reel 1", Fig. 2 presents the full report of the 3DSSPP evaluation.

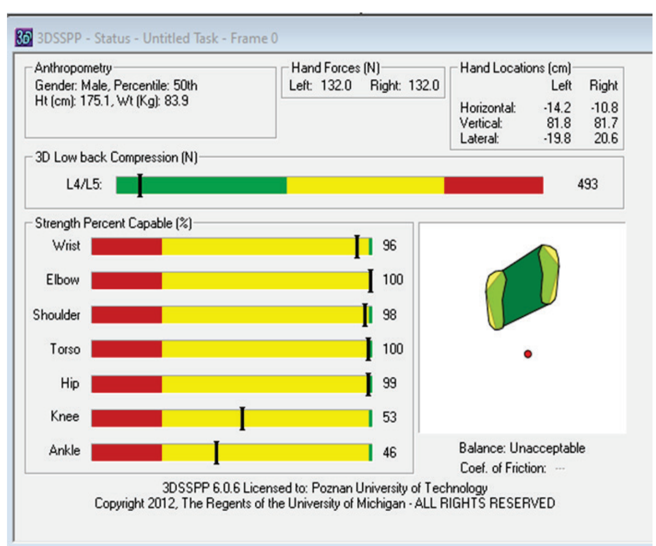


Figure 2 3DSSPP assessment result for the activity "Pulling the reel 1"

It can be stated that the Mo-Cap reading results are similar to the camera-recorded performance of the activity. Similarly, the model presented using 3DSSPP reflects the actual activities performed by the employee. It is also worth noting that Mo-Cap can be used to read the body position when performing activities at high speed and requiring the employee to apply a lot of force.

5 DISCUSSION

In determining the possibility of using Mo-Cap for ergonomic analyses, attention should be paid to errors and irregularities that may occur during the testing (and also occurred in the analyzed example).

1) While reading the data and tracking the 3D model generated in the program, an irregularity was noticed - one of the sensors lost connection with the transmitter, which resulted in an incorrect starting position of one of the joints (Fig. 3).

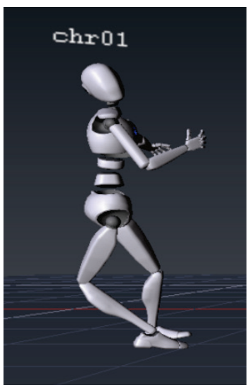


Figure 3 Uncalibrated sensor view shots [source: Axis Studio Program]

2) Another limitation was the lack of the ability to read the angles between the joints. This function was necessary for precise ergonomic assessment using Motion Capture technology. The Axis-studio software, which is the target software for the Neuron Perception mapping set, does not assume such a function. After multiple attempts, it was decided to use other programs for reading the mapped data.
3) Technical problems were encountered during the measurements. The equipment required frequent calibration, which was not always successful. Because of incorrect connection of the sensors with the transfer, it was necessary to repeat calibration attempts, which required additional time (Fig. 4).
4) In the analyzed case, bands requiring additional attachments were used, with the help of which the sensors could be attached in appropriate places. The process of dressing the employee in bands and installing the sensors turned out to be a time-consuming task, and it required the input of the employee and a third party who had to attach the sensors to the employee's body and activate them.
5) The unreliability of the sensors and their disconnection during the test turned out to be one of the greatest limitations. In the event that the test was not repeated and recorded with a camera, it could have been impossible to obtain data for processing.

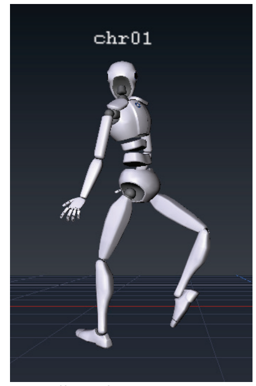


Figure 4 A shot showing the effect of losing connection between the sensor and the transmitter [source: Axis Studio Program]

Based on the analyzed example, it is also possible to indicate the positive aspects of using Mo-Cap in ergonomic assessment:

1) The employees were interested in the course of the research using Mo-Cap. The generated 3D model aroused the interest of the company, and the presentation of the results gained additional attention and curiosity. The 3D model was used to present the entire process, based on which it was possible to explain the source of the reported ergonomic problems.
2) Direct contact with employees, which was necessary due to the specific nature of the research, conducted using Motion Capture technology, turned out to be extremely valuable. Thanks to this, it was possible to overcome communication barriers and obtain additional, often very useful information about the course of the work process. Employees were more willing to share their observations, which allowed for a deeper analysis of the ergonomics of their workstation.
3) Employers, observing the presented silhouette model generated by Neuron Perception software, could see that employees' comments regarding their workstations were justified. Thanks to precise visualization, it was possible to notice ergonomic irregularities that could have been previously underestimated.
4) Another benefit of being able to show a 3D model of work is the possibility of educating employees. The 3D model provided a clearer visual aid for employees to identify ergonomic improvements in their workspace. This type of tool allows to indicate places where work is not performed in accordance with ergonomic principles, which is often omitted in traditional analyses.

A further direction of work on the undertaken research could be to identify the possibilities of using artificial intelligence to overcome the problem of measuring angles in the application of motion capture in ergonomics.

6 CONCLUSIONS

The analysis of the study results showed both the potential and limitations of using Motion Capture technology in ergonomics, which allows for a better understanding of its applications in practice and in systemic safety management in an organization. It can be undoubtedly stated that it brings great benefits, especially in modeling the work of an employee, which can then be translated into standard methods of ergonomic assessment. Unfortunately, such translation must be done independently, which may require additional time in the analyses. A major barrier to overcome is certainly the lack of precise reading of the angles of employee body segments, which is what most ergonomic assessments are based on. This creates a requirement for additional software. It can be noted that the recognition of the possibilities of using Mo-Cap in ergonomics is the subject of scientific research. Researchers note similar difficulties in implementing this technology, at the same time they note its importance in an individual approach to the assessment of each employee (which, for example, estimation methods do not provide). The potential solution to the limitations is the use of additional supporting software or a detailed definition of the purpose of the Mo-Cap assessment and the scope of applicability [20, 21].

To sum up, it can be stated that the use of Motion Capture in ergonomics is possible and beneficial from a practical point of view, if appropriate resources are established and additional elements are provided to enable reliable assessments. This may require the assessor to perform a time-cost calculation and decide whether the benefits outweigh the resources needed to eliminate the barriers. Certainly, in some cases (e.g., a systemic assessment of all workstations in an organization), it may turn out that the use of Mo-Cap will be problematic due to the long time required to set up and connect the equipment. In other cases, it may be an advantage (e.g., getting employees interested in the assessment process or convincing the company's management to change by visually presenting problems). These benefits are of particular importance in systemic safety management, which includes ergonomics. It requires the involvement of all participants in the organization to be carried out successfully and improved constantly.

7 REFERENCES

[1] Colim, A., Faria, C., Braga, A. C., Sousa, N., Rocha, L., Carneiro, P., Costa, N. & Arezes, P. (2020). Towards an Ergonomic Assessment Framework for Industrial Assembly Workstations - A Case Study. *Applied Scinces, 10*, 3048, https://doi.org/10.3390/app10093048

[2] Tomelleria, F., Sbaraglia, A., Piacariello, F. & Pilati, F. (2024). Safe Assembly in Industry 5.0: Digital Architecture for the Ergonomic Assembly Worksheet. *Procedia CIRP, 127*, 68-73. https://doi.org/10.1016/j.procir.2024.07.013

[3] Butlewski, M., Czernecka, W., Szczepaniak, A., Pojasek, M. & Baran, M. (2019). Practical implications on ergonomic assessments resulting from EN16710-2 - ergonomics methods: A methodology for work analysis to support design. *Zeszyty Naukowe Małopolskiej Wyższej Szkoły Ekonomicznej w Tarnowie, 43*(3), 127-142. https://doi.org/10.25944/znmwse.2019.03.127142

[4] Joshi, M. & Deshpande, V. (2019). A systematic review of comparative studies on ergonomic assessment techniques. *International Journal of Industrial Ergonomics, 74*, 102865. https://doi.org/10.1016/j.ergon.2019.102865

[5] Lim, S. & D'Souza, C. (2020). A narrative review on contemporary and emerging uses of inertial sensing in occupational ergonomics. *International Journal of Industrial Ergonomics, 76*, 102937. https://doi.org/10.1016/j.ergon.2020.102937

[6] Okkonen, J., Heimonen, T., Savolainen, R. & Turunen, M. (2018). Assessing Information Ergonomics in Work by Logging and Heart Rate Variability. In: Ahram, T. & Falcão, C. (eds) *Advances in Usability and User Experience*. AHFE 2017. Advances in Intelligent Systems and Computing, 607. Springer, Cham. https://doi.org/10.1007/978-3-319-60492-3_41

[7] Lowe, B. D., Dempsey, P. G. & Jones, E. M. (2019). Ergonomics assessment methods used by ergonomics professionals. *Applied Ergonomics, 81*, 102882. https://doi.org/10.1016/j.apergo.2019.102882

[8] Tiacci, L. & Mimmi, M. (2018). Integrating ergonomic risks evaluation through OCRA index and balancing/sequencing decisions for mixed model stochastic asynchronous assembly lines. *Omega, 78*, 112-138. https://doi.org/10.1016/j.omega.2017.08.011

[9] Restuputri, D. P., Masudin, I. & Putri, A. R. C. (2020). The comparison of ergonomic risk assessment results using job strain index and OCRA methods. *IOP Conf. Series: Materials Science and Engineering*, 821. https://doi.org/10.1088/1757-899X/821/1/012029

[10] Yazdanirad, S., Khoshakhlagh, A. H., Habibi, E., Zare, A., Zeinodini, M. & Dehghani, F. (2018). Comparing the Effectiveness of Three Ergonomic Risk Assessment Methods-RULA, LUBA, and NERPA-to Predict the Upper Extremity Musculoskeletal Disorders. *Indian Journal of Occupational and Environmental Medicine, 22*, 17-21. https://doi.org/10.4103/ijoem.IJOEM_23_18

[11] Teymourian, K., Tretten, P., Seneviratne, D. & Galar, D. (2021). Ergonomics evaluation in designed maintainability: case study using 3 DSSPP. *Management Systems in Production Engineering, 29*(4), 309-319. https://doi.org/10.2478/mspe-2021-0039

[12] Zhang Y., Wu X., Gao J., Chen J. & Xv X. (2019). Simulation and Ergonomic Evaluation of Welders' Standing Posture Using Jack Software. *International Journal of Environmental Research and Public Health, 16*, 4354. https://doi.org/10.3390/ijerph16224354

[13] Fernández, M. M., Fernández, J. A., Bajoa, J. M. & Delrieuxa, C. A. (2020). Ergonomic risk assessment based on computer vision and machine learning. *Computer & Industrial Engineering, 149*, 106816. https://doi.org/10.1016/j.cie.2020.106816

[14] Donisi, L., Cesarelli, G., Pisani, N., Ponsiglione, A. M., Ricciardi, C. & Capodaglio, E. (2022). Wearable Sensors and Artificial Intelligence for Physical Ergonomics: A Systematic Review of Literature, *Diagnostics, 12*, 3048. https://doi.org/10.3390/diagnostics12123048

[15] Qin, R., Ciu, P. & Muhsin, J. (2024). Research Progress of Automation Ergonomic Risk Assessment in Building Construction: Visual Analysis and Review. *Buildings, 14*(12), 3789. https://doi.org/10.3390/buildings14123789

[16] Salisu, S., Ruhaiyem, N. I. R., Eisa, T. A. E, Nasser, M., Saeed, F. & Younis, H. A. (2023). Motion Capture Technologies for

Ergonomics: A Systematic Literature Review. *Diagnostics, 13*, 2593. https://doi.org/10.3390/diagnostics13152593

[17] https://neuronmocap.com/blogs/mocap101/the-different-types-of-mocap-systems-and-how-they-work?srsltid=AfmBOor77KeQ5v6iPO_4wIro_BP3mIWVp11Fyn9ugviYhHlZ7NTSJtPG, accessed: 29.12.2024.

[18] Igelmo, V., Syberfeldt, A., Högberg, D., García Rivera, F. & Pérez Luque, E. (2020). Aiding Observational Ergonomic Evaluation Methods Using MOCAP Systems Supported by AI-Based Posture Recognition. *Advances in Transdisciplinary Engineering, 11*, 419-429. https://doi.org/10.3233/ATDE200050

[19] Wu, Y., Tao, K., Chen, Q., Tian, Y. S. & Sun, L. (2022). A Comprehensive Analysis of the Validity and Reliability of the Perception Neuron Studio for Upper-Body Motion Capture. *Sensors, 22*(18), 6954. https://doi.org/10.3390/s22186954

[20] Brosche, J., Wackerle, H., Augat, P. & Lodding, H. (2024). Individualized workplace ergonomics using motion capture. *Applied Ergonomics, 114*. https://doi.org/10.1016/j.apergo.2023.104140

[21] Herzog, V., Buchmeister, B., Park, J. & Kaya, Ö. (2024). Enhancing workplace safety and ergonomics with motion capture systems: Present state and a case study. *Advances in Production Engineering & Management, 19*(3), 333-346. https://doi.org/10.14743/apem2024.3.510

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Sustainable Corrosion Protection of Aluminium Alloys – Life Cycle Assessment of Established and Innovative Coating Processes

Juergen M. Lackner*, Reinhard Kaindl, Sara Carniello, Simon Chwatal, Max Stummer

Abstract: Aluminium alloys are highly valued for their lightweight properties. However, their susceptibility to corrosion, particularly in chloride-containing environments, presents significant challenges especially when considering "green" sustainable processing routes. Applying ISO 14040 life cycle assessment (LCA) approach, traditional surface treatment techniques (anodization, conversion coatings, organic paints, plasma activated chemical vapour deposition in vacuum) are compared for the first time to innovative approaches such as Atmospheric Pressure Plasma Deposition (APPD). Although highly conservative assumptions are taken in the life cycle inventory, the greenhouse gas emissions of APPD are clearly lower than in the other technologies, especially because of the higher efficiency in feedstock use, the higher throughput, and the plasma-and air-supported oxidation of CH_4, formed during dissociation of the silicon organic precursor. By achieving corrosion properties of cerium-doped APPD silicone coatings similar to the state-of-the-art and elimination of repainting as for organic paints, APPD is at the forefront of sustainable processing.

Keywords: aluminium alloys; atmospheric pressure plasma deposition; coatings; corrosion protection; life cycle analysis

1 INTRODUCTION

The corrosion behaviour of aluminium alloys arises from their microstructural and surface characteristics. AlSi10Mg, when produced using conventional casting or advanced additive techniques like powder bed fusion (PBF), often has a microstructure that includes silicon particles distributed in the aluminium matrix [1]. In PBF-processed alloys, rapid solidification can lead to fine cellular or dendritic microstructures, which enhance strength but may introduce porosity and surface roughness. These microstructural features create localized galvanic cells and make the material more prone to pitting and general corrosion [2]. Moreover, the intrinsic oxide layer (Al_2O_3) that forms on aluminium provides only moderate protection and is susceptible to degradation in acidic or highly alkaline environments [3].

Traditional corrosion protection techniques for aluminium alloys include organic coatings, anodization, and conversion coatings [4]. Coatings are evaluated through standardized methods such as ISO 9227 for salt spray resistance and ISO 2409 for adhesion. Organic coatings, typically applied as paints or primers, form a physical barrier to environmental factors [5]. While providing initial corrosion resistance, organic coatings may suffer from permeability to moisture and oxygen, eventually leading to crevice corrosion at the interface to the substrate. Repainting every 5-10 years is common. Anodization as an electrochemical process generates a thick oxide layer on the aluminium surface [6]. The layer's porosity can be reduced by subsequent sealing treatments to enhance barrier properties (e.g., in hot water or nickel acetate solution). Evaluations using EN 12373 standards reveal that anodized coatings exhibit good corrosion resistance and surface hardness. However, anodization is sensitive to surface imperfections and can amplify defects, especially in components with rough surfaces. Further, acidic solutions require neutralization and hazardous waste disposal. Conversion coatings, such as chromate or phosphate coatings, provide active corrosion protection by chemically altering the substrate's surface [7]. While chromate coatings have excellent self-healing capabilities, their use is restricted due to environmental and health concerns [8]. Recent efforts have explored non-toxic alternatives like cerium-based conversion coatings [9], which show promise in mitigating pitting corrosion.

Sol-gel technology involves the application of colloidal solutions that solidify into thin films upon drying and curing for crosslinking at elevated temperatures or UV radiation [10]. Mainly silicon organic precursors are used, mixed with solvents. However, their relatively limited thickness (a few 100 nanometres due to cracking risks) and durability in extreme conditions restrict their industrial use. Similarly, plasma activated chemical vapour deposition (PACVD) relies on silicon organic precursors, being polymerized under vacuum conditions using radio-frequency, microwave or kHz pulsed plasma at the components surfaces in a thickness regime of typically 1 µm thickness [11]. Pre-treatments increase the coating adhesion, while deposition in cavities is complex.

Atmospheric pressure plasma deposition (APPD) is an innovative surface coating technology at the industrial breakthrough, overcoming main limitations of vacuum based processing of PACVD, if working with vaporized or aerosolized precursor liquids [12]. The APPD process does not require vacuum systems, making it economically and operationally attractive. Fig. 1 illustrate the setup and operation of the APPD system based on robot mountable plasma jets, highlighting its capability to process components with complex 3D geometries [13]. The admixture of organic precursors or aerosols (like polymerize-able hexamethyl disiloxane (HMDSO) with e.g. Ce containing salt or nanoparticle containing aqueous or alcoholic solutions), done directly to the atmospheric pressure plasma or to the subsequent thermal "afterglow" zone in front, leads first to fragmentation of the organic molecules as basis for cross-linking after deposition of silicones in inert or silicates in oxygen containing process gas on the substrate surface.

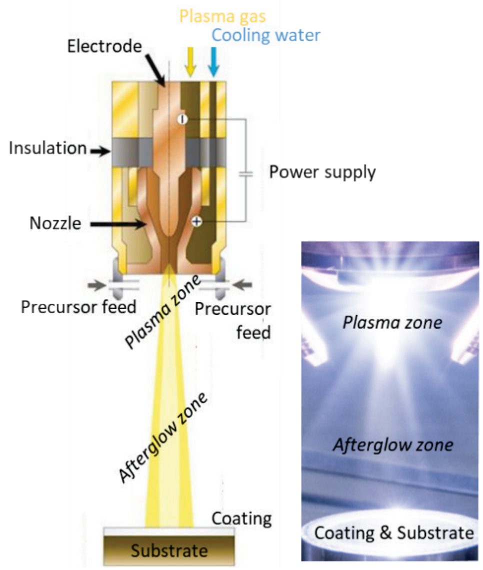

Figure 1 Principle of plasma jet based APPD for coating deposition: (left) Plasma formation by high current discharge within a cathode-anode slit at simultaneous high inert gas flow, transporting the excited species (Ar ions, electrons) to the open air in front of the jet. (right) Photograph from process control. [13]

The APPD coatings with high barrier properties are particularly effective due to their ability to incorporate active corrosion inhibitors like cerium ions from aqueous aerosols. The mechanism involves the formation of cerium hydroxides and oxides at defect sites, which suppress corrosion propagation, as shown by the excellent performance in salt spray tests of PBF components (Fig. 2a) and the dense barrier formation in impedance spectroscopy (Fig. 2b). In comparison, they are outperforming traditional coatings in both corrosion resistance and adhesion in chloride-rich environments.

The comparison of APPD with traditional methods also extends to environmental and economic aspects. APPD coatings are free of hazardous materials like hexavalent chromium, aligning with regulatory frameworks such as REACH and RoHS. The process's energy efficiency and scalability further enhance its industrial feasibility, particularly for applications requiring high-throughput and cost-effective solutions, which is shown in the following by an extended LCA in detailed comparison to state-of-the-art PACVD in vacuum and using literature data to conventional processes.

2 EXPERIMENTAL

The environmental sustainability of coating technologies can be evaluated systematically by LCAs using standardized methodology (e.g. ISO 14040), assessing the environmental impacts of a product or process over its entire lifecycle from raw material extraction to end-of-life disposal. Based on own data on the typical annual performance of a APPD plant for deposition of 1 µm thick coatings in 1 shift operation, 7200 m²/year coating area were defined, i.e. for a 10 years equipment use 72,000 m² coated surface. The deposition of coatings with comparable properties by PACVD requires ~3.8 units because of the longer process times. Salt spray testing of rough PBF AlSi10Mg components revealed, that the specified minimum lifetime is fulfilled by such 1 µm coating thickness, being basis for the comparative assumption for the conventional technologies.

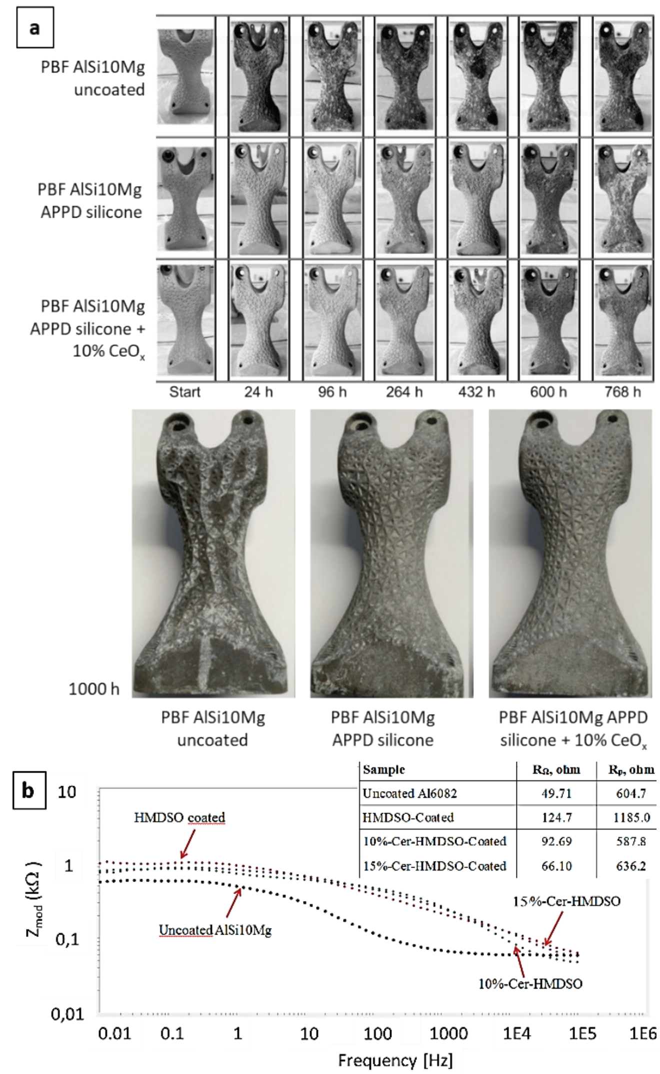

Figure 2 (a) PBF AlSi10Mg components with rough, ball-blasted surfaces after up to 1000 h salt spray testing (ISO 9227) (b) Active corrosion protection effect (barrier effect & healing of defect sites) of APPD silicone coatings revealed by impedance spectroscopy measurements. [13]

The Life Cycle Inventory (LCI) on all inputs (materials, energy) and outputs (waste, emissions) throughout the lifecycle stages is given in Tab. 1, laying the focus especially on the initial processing and excluding the end-of-life of the coated component (i.e. due to negligible effects of such silicone coatings in metal recycling) and of equipment (cradle-to-gate approach).

The analysed impacts include greenhouse gas emissions, resource depletion (fossil and minerals/metals), water consumption, taking the impact factors from the Environmental Footprint method. Resource depletion-fossil and water consumption follow the same trend as GHG emissions and are thus not reported. Background data have been taken from ecoinvent v3.10 database [14].

Table 1 LCI for silicone coating processes and equipment – APPD vs. PACVD

Parameter	APPD	PACVD
Functional Unit (FU)	1 µm silicone on 7,200 m² (annually) and 72,000 m² (equipment life)	
Annual Energy Use (MWh)	144	2,080
Gas Consumption (m³/a)	18,000 Ar	1,043 N_2
HMDSO Feedstock Use Efficiency (%)	60	50
Totally required HMDSO Precursor (kg/a)	216	432
Methane Emissions (CH_4, kg/a)	42,7	85,3
Equipment Lifespan (years)	10	10
Number of required Units (based on achievable deposition rate to enable 7200 m²/a)	1	~3,8
Metals used per Unit – Steel / Stainless Steel / Copper / Brass / Aluminium / Titanium (kg)	1314 / 74 / 81 / 6 / 288 / 0	115 / 460 / 86 / 6 / 115 / 6
Polymers / Electronics used per Unit (kg)	79 / 34	63 / 259
Maintenance Components per Year	30 plasma nozzles, 5 coatings	Protective shields (1 per year), pumps (1 each 4 years)

3 RESULTS & DISCUSSION

The assessment of potential environmental impacts targets as main indicator the greenhouse gas emissions (GHG), for which both the equipment manufacturing (raw materials and device manufacturing) and the coating deposition itself is taken under consideration; excluded are emissions for aluminium substrate components are not considered, being similar for the envisaged coating processes. Tab. 2 shows the accurate calculation results for APPD and PACVD and published average values for the state-of-the-art technologies [15-21].

Table 2 Energy requirements and emissions for coating technologies for corrosion protection of aluminium [12-18]

Parameter	APPD	PACVD	Anodization	Organic Coatings	Conversion Coatings	Sol-Gel Coatings
Annual Energy Use (MWh) for 7200 m²	144	2,080	400	50	120	100
CH_4 Emissions (kg/year)	42.7	85.3	Negligible for the surfacte modification step (i.e., excluding the production of feedstock)			
GHG Emissions (kg CO_2e/m²)	1–2	6–8	5–7 (with sealing)	8–12	2–3 (cerium-based)	1–2
Material Efficiency (%)	60	50	Moderate	Low	High	Moderate
Waste Generation	Low	Moderate	Moderate	High	Low	Low

Based on the precise insight in PACVD and APPD processes, GHG as well as the abiotic depletion potential (ADP) can be well split to the contributions from the coating device (including an annual depreciation of construction materials and manufacturing processes for the device), from necessary spare parts in maintenance, and from the processing step (i.e. the coating application and the contributions from required HMDSO precursor and gas feedstock) (Fig. 3).

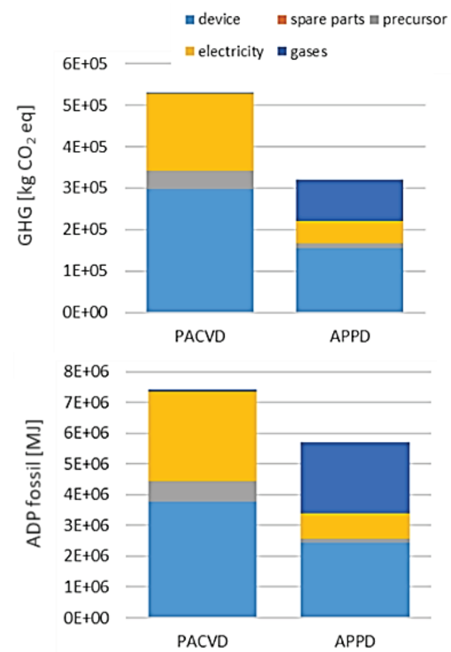

Figure 3 Comparison of GHG (above, CO_2 eq) and ADP (below) for PACVD and APPD, related to a functional unit ("coating device")

Well visible is the high contribution of the devices and the electricity necessary for PACVD processing as well as the high GHG contribution from the precursors. Importantly, the given data is shown per functional unit, which means for comparable annual coating area of 7200 m² 3.8 PACVD units need to be applied, while a single APPD unit is sufficient. In contrast, the construction of one APPD device is much less demanding in terms of materials. Further, the lower electricity consumption during processing as well as the minimization of CH_4 formation as exhaust gas, due the precursor molecules leaving the plasma reduce significantly the GHG emissions. Additionally, the efficiency in material use is at least 10% higher for APPD than for PACVD (50 vs. 60%).

Having a closer look on the contributions of the various materials used for the device construction, some significant differences are visible (Fig. 4). PACVD vacuum coating demands a heavy stainless steel vacuum chamber and a massive carbon steel frame, while constructions for APPD are based on carbon steel for the frame too, but the deposition enclosure to prevent exhaust gas emission directly to the operators and the used manipulation robots are mainly based on aluminium.

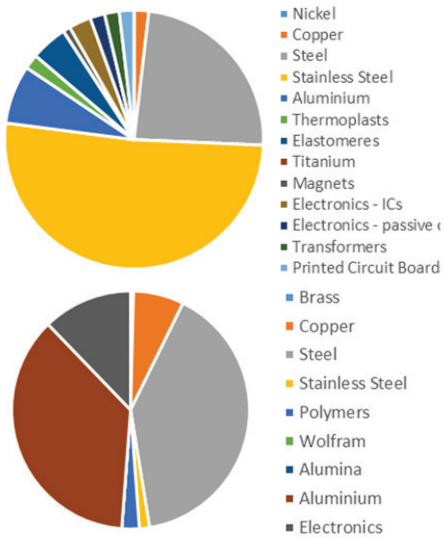

Figure 4 Comparison of GHG (CO_2 eq) on the materials used for construction PACVD (above, ~297,000 kg CO_2 eq in total) and APPD (below, ~156,000 kg CO_2 eq) for industrially-scaled coating deposition

Comparing the results with state-of-the-art processes (Tab. 2), based on literature provided data [15-21], the reasons for the observed differences of conventional processes and PACVD to APPD are exemplary in terms of

- energy requirements: demands of heating for anodization (incl. sealing) and drying / curing of organic paints
- GHG emissions; during device manufacturing and processing
- material utilization and waste: localized APPD deposition with very low overspray compared to typically 20-30% overspray in compressed-air spraying of organic and sol-gel coatings
- material footprint; for the construction of tools
- by-products and emissions: acidic and metallic effluents from solvents in organic and sol-gel coatings during sealing (incl. potentially hazardous nickel acetate)
- process complexity and scalability: extensive surface pre-treatment in anodization for uniform defect-free oxide layer formation, and a strong environmental and humidity impacts on sol-gel curing.

4 CONCLUSIONS

Corrosion protection of aluminium alloys is crucial for their long service-life, but a quite complex task with sustainable technologies with no environmental harms. As shown by first time LCAs for protective silicone coatings, the innovative APPD processes combines high ecologic potentials compared to state-of-the-art vacuum PACVD and other established processes from literature. Based on salt spray test results, the demanded service life is easily achieved by high-performance, high-throughput APPD treatments. Comparatively, PACVD faces limitation in scalability due to required vacuum conditions, while conversion coatings, anodization and organic coatings require enhancements to meet modern sustainability standards by emissions, durability and hazards.

Nevertheless, the detailed view on the device construction and use for silicone, Cerium doped corrosion protective coating deposition provides also insight into potential areas for further decrease of GHG emissions: Rethinking device construction to minimize the impacts from the machinery hardware and redesign processes to reduce Argon as process gas, either by gas recycling or use of less clean gas, can be drawn for future development steps.

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5 REFERENCES

[1] Laieghi, H., Kvvssn, V., Butt, M. M., Ansari, P., Salamci, M. U., Patterson, A. E. & Salamci, E. (2024). Corrosion in laser powder bed fusion AlSi10Mg alloy. *Engineering Reports, 6*(10), e12984. https://doi.org/10.1002/eng2.12984

[2] Gatto, A., Cappelletti, C., Defanti, S. & Fabbri, F. (2023). The Corrosion Behaviour of Additively Manufactured AlSi10Mg Parts Compared to Traditional Al Alloys. *Metals, 13*(5), 913. https://doi.org/10.3390/met13050913

[3] Korzekwa, J. (2023). Modification of the structure and properties of oxide layers on aluminium alloys: A review. *Reviews on Advanced Materials Science, 62*(1), 20230108. https://doi.org/10.1515/rams-2023-0108

[4] Revilla, R. I., Verkens, D., Rubben, T. & De Graeve, I. (2020). Corrosion and corrosion protection of additively manufactured aluminium alloys—A critical review. *Materials, 13*(21), 4804. https://doi.org/10.3390/ma13214804

[5] Musa, A. Y. (2012). Corrosion protection of Al alloys: Organic coatings and inhibitors. *Recent Researches in Corrosion Evaluation and Protection,* 51-66.

[6] Paz Martínez-Viademonte, M., Abrahami, S. T., Hack, T., Burchardt, M. & Terryn, H. (2020). A review on anodizing of aerospace aluminum alloys for corrosion protection. *Coatings, 10*(11), 1106. https://doi.org/10.3390/coatings10111106

[7] Becker, M. (2019). Chromate-free chemical conversion coatings for aluminum alloys. *Corrosion Reviews, 37*(4), 321-342. https://doi.org/10.1515/corrrev-2019-0032

[8] Zehra, S., Mobin, M. & Aslam, J. (2022). Chromates as corrosion inhibitors. In *Inorganic anticorrosive materials*, 251-268. Elsevier. https://doi.org/10.1016/B978-0-323-90410-0.00014-3

[9] You, G., Hou, J., Xu, Y., Miao, L., Ao, Y. & Xing, B. (2021). Surface properties and environmental transformations controlling the bioaccumulation and toxicity of cerium oxide nanoparticles: a critical review. *Reviews of Environmental Contamination and Toxicology, 253*, 155-206. https://doi.org/10.1007/398_2020_42

[10] Kumar, D. S. A., Viswanath, B. A. & Raghul, P. (2024). A review of preparation and characterization of sol-gel coating for corrosion mitigation. *Int. J. Eng. Technol. Manag. Sci., 8*(2). https://doi.org/10.46647/ijetms.2024.v08i02.002

[11] Mascagni, D. B. T., Souza, M. E. P. D., Freire, C. M. D. A., Silva, S. L., Rangel, R. D. C. C., Cruz, N. C. D. & Rangel, E. C. (2014). Corrosion resistance of 2024 aluminum alloy coated with plasma deposited a-C: H: Si: O films. *Materials Research, 17*, 1449-1465. https://doi.org/10.1590/1516-1439.289014

[12] Jang, H. J., Jung, E. Y., Parsons, T., Tae, H. S. & Park, C. S. (2021). A review of plasma synthesis methods for polymer films and nanoparticles under atmospheric pressure conditions. *Polymers, 13*(14), 2267. https://doi.org/10.3390/polym13142267

[13] Lackner, J. M., Kaindl, R., Schwan, A., Meier, B., Augl, S., Gumus, S., Hinterer, A. & Stummer, M. (2021) Atmosphärische Plasmabeschichtung mit aktiven Korrosionsschutz-Beschichtungen für 3D-Druck-Aluminium-Bauteile. *Jahrbuch Oberflächentechnik, 2021*, Bd. 77. (in German). https://doi.org/10.12850/9783874803700.007
[14] For software details see: https://ecoinvent.org/ecoinvent-v3-10/
[15] Priarone, P. C., Catalano, A. R., & Settineri, L. (2023). Additive manufacturing for the automotive industry: on the life-cycle environmental implications of material substitution and lightweighting through re-design. *Progress in Additive Manufacturing, 8*(6), 1229-1240. https://doi.org/10.1007/s40964-023-00395-x
[16] Rolseth, A., Carlsson, M., Ghassemali, E., Caro, L. P. & Jarfors, A. E. (2024). Impact of functional integration and electrification on aluminium scrap in the automotive sector: A review. *Resources, Conservation and Recycling, 205*, 107532. https://doi.org/10.1016/j.resconrec.2024.107532
[17] Paiano, A., Gallucci, T., Pontrandolfo, A., Lagioia, G., Piccinno, P. & Lacalamita, A. (2021). Sustainable options for paints through a life cycle assessment method. *Journal of Cleaner Production, 295*, 126464. https://doi.org/10.1016/j.jclepro.2021.126464
[18] Moign, A., Vardelle, A., Legoux, J. G. & Themelis, N. J. (2009). LCA comparison of electroplating and other thermal spray processes. *Expanding Thermal Spray Performance to New Markets and Applications*, 1207-1212. https://doi.org/10.31399/asm.cp.itsc2009p1207
[19] Salonitis, K., Jolly, M., Pagone, E. & Papanikolaou, M. (2019). Life-cycle and energy assessment of automotive component manufacturing: The dilemma between aluminum and cast iron. *Energies, 12*(13), 2557. https://doi.org/10.3390/en12132557
[20] Borgaonkar, A. & McNamara, G. (2024). Environmental Impact Assessment of Anti-Corrosion Coating Life Cycle Processes for Marine Applications. *Sustainability, 16*(13), 5627. https://doi.org/10.3390/su16135627
[21] Négré, P., Brusciotti, F., Parrab, M. B., Duránc, A., Martínc, Y. C., Hamond, L. & Halute, J. (2014). Ecoprot, eco-friendly corrosion protecting coating of aluminium and magnesium alloys, an ECO innovation project. *Chemical Engineering*, 41.

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Calculation Driven Parametric Design of a Mechanical Assembly on the Example of a Hook Block

Filip Stanić, Daniel Miler, Matija Hoić*

Abstract: Parametric modeling is a common technology in numerous CAD software packages. One of the advantages of applying parametric modeling is the possibility of forming families of models that share a geometric structure with differences in dimensions. The user is left to generate a new set of dimensions. This paper presents an investigation of the possibility of upgrading the parametric modeling system with the calculation of the mechanical components in the form of a computer program. The user enters a set of operational requirements on the target mechanical assembly based on which the computer program calculates the needed dimensions of mechanical components to fulfill given requirements. The results of these calculations are used to parameterize the model. This approach is demonstrated using the example of a Hook Block model developed within the 3DExperience (3DX).

Keywords: CAD; engineering template; generic model; parametric modelling; product families

1 INTRODUCTION

Different CAD systems have become a mainstay of tools for industrial design in the past decades and have become highly developed software solutions that offer robust and powerful means for product development. However, further development is still ongoing as new potential for production improvement appears in combination with other technologies. Some of the development relates to long-standing problems such as the transfer of models from one CAD system to the other [1], the recent proliferation of AI tools presents a possibility of combining AI and CAD to generate new product design [2] or to combine AI, CAD, VR, and additive manufacturing to expedite the design process [3].

Apart from the development of the structure of the CAD model, the question of numerical values for dimensions, choice of material, and similar properties remains. Software solutions for engineering calculations are also heavily applied in everyday work. Hence, the idea of combining these two types of tools is heavily investigated. Examples include the design of single components such as gears by programming ACMA standards using Visual Basic where the results are supplied to the gear model developed in SolidWorks [4], but also for the design of assemblies such as the computation of heat transfer used to parametrize heat exchanged CAD model [5].

In both cases, the structure of the product remains unchanged and only the dimensions are affected by the computation. However, cases of systems with structure variations based on input parameter values are also common. One used approach is to develop a CAD assembly model in *ProEngineer* with all possible options for individual components, such as the case of automotive steering wheel joints design presented in [6]. Based on the results of calculations performed in Excel, out of all structural options for a single component, a chosen option is parameterized while all other options are suppressed.

It may be argued that this approach has two disadvantages. Firstly, additional computational resources are needed to handle all non-used options. Secondly, in the case of sharing such a model outside of the organization with a potential client, significant proprietary knowledge may be unwillingly shared. This paper explores an alternative approach by creating a parametric model and the so-called engineering template of the Hook Block with the ropes, inside the CATIA V6 module of 3DExperinence. The engineering templates are based on parametrically constructed generic models (generic models). Generic Product) of certain standardized assemblies or parts. The generic model itself contains all the necessary calculations necessary for its creation, all the catalogs of standard parts that can be used in it and is designed to adapt to the input parameters or geometry specified by the user (end user).

2 HOOK BLOCK

Fig. 1 shows a standard Hook Block with marked parts for which it is necessary to define a sizing algorithm, which includes the Hook itself, bearing, bracket, nut, support plate, shaft, and pulley assembly. The structure and standard dimensions have been selected according to DIN 15400, DIN 15401, DIN 15402, and DIN 15412. According to the standards, standards Hook sizes are defined using a value called Hook number *HN*, which unambiguously determines their shape and dimensions. Depending on the Hook Number, the load class and the permissible load of the Hook depend on the load class, the material, and the safety factor. The load class considers the frequency of application and the spectrum of loads to which the part is exposed.

Once the standard Hook is chosen, all other standard parts of the Hook Block are then selected according to the Hook Number of the chosen Hook. In the final model, the user will enter/select the values of the three named parameters, the model will conduct the required calculation of the Hook Number, and all the standard parts will be chosen automatically.

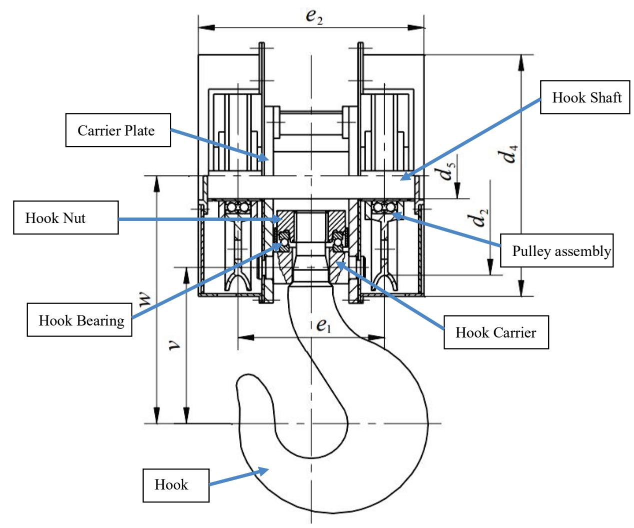

Figure 1 Hook Block structure

3 INPUT PARAMETERS

After defining the basic calculation algorithm, it is necessary to determine which input parameters the user will enter, and what is their range. This will further define which branches are needed in the calculation, and what the configurations in certain ranges of these parameters will look like.

The main input parameters of the model will be the maximum weight of the load, the quality of the material, and the drive group. The latter can be defined according to the purpose of the crane, which in this case was carried out using the DIN 15018 and HRN EN 13001-1 standards. Additional parameters that the user selects in principle include:

- Type of Hook,
- The shape of the rope assembly,
- Configuration of ropes,
- Type of rope, etc.

As this paper seeks to show the very potential of using engineering templates, the above additional parameters will not be used as a choice option. Rather, these options will be chosen according to programmed criteria.

Furthermore, the model works inside a certain range of values that the user can enter. The lower limit of the load capacity is set at 2 t, since below that load capacity there are significant changes in the geometry of the Hook carrier which is out of scope for this paper. A maximum weight of 50 t has been selected for the upper load limit, which covers the range of a typical crane. After determining the input parameters and their ranges, it is necessary to define how the calculation or structure of the Hook Block will change depending on which part of the range the values set by the user are located.

The main influence on the design and structure of the assembly is the number and arrangement of load-bearing ropes, and they in turn depend on the maximum load capacity of the Hook Block. To reduce the complexity of the model, the number of wearable ropes is limited to 1, 2 or 4.

It is necessary to determine which load capacities a certain number of ropes correspond to. The selection will be guided by established industry practice. Due to the simpler selection of configurations, the load capacities are implemented in approximately equivalent ranges of Hook numbers (Tab. 1).

Table 1 Recommended number of Hook pulleys as a function of Hook number [7]

n	1	2	4
Hook number	2,5...6	8...25	32...80

4 3DEXPERIENCE SOFTWARE PACKAGE

3DX CATIA is structured in several applications. The following are used herein:

- Part Design Essentials (part modeling),
- Generative Wireframe & Surface (enables usage of wireframe geometry i.e. skeleton model),
- Assembly Design,
- Engineering Rules Capture (adds rules and reactions to the model, written in Enterprise Knowledge Language (EKL)),
- Structure Design and Steel Outfitting Design (standard profiles and parts),
- Collaborative Lifecycle (managing of elements within the catalog).

Fig. 2 shows the data flow diagram of the proposed calculation driven parametric design tool. Details are described in the following sections.

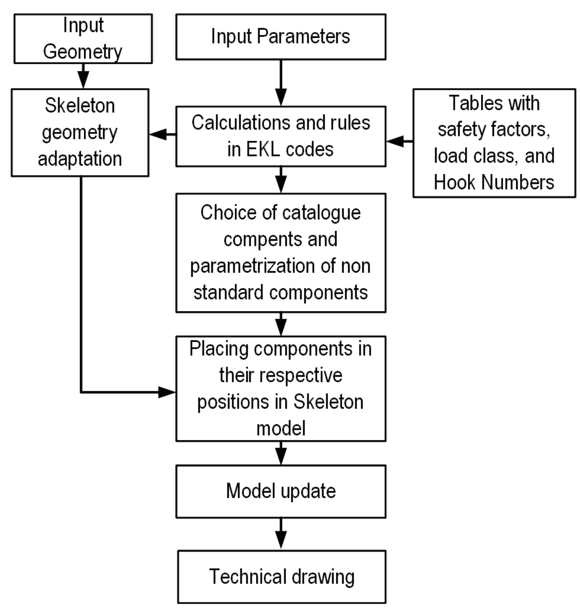

Figure 2 Flow diagram of developed calculation driven parametric design tool.

5 ENGINEERING TEMPLATE

Within 3DX CATIA there is a type of model called *Engineering Template* which is a customizable product model based on the principle of parametric modeling. It can adjust its geometry according to the needs of the user by simply changing the input data and the set parameters.

The advantage of an Engineering Template over other models, such as *PowerCopy* or *User Feature*, is that the model automatically adjusts to user-defined input data when instantiated and is not just a copy of a generic model.

The main disadvantage is the need for a complete definition of input data, most often based on geometric elements and parameters, and the need for the user to accurately prepare the circuit before instantiation. With *PowerCopy* or *User Feature*, the instantiation process is much simpler and requires less preparation, which reduces the possibility of errors. Also, the process of creating an *Engineering Template* is more complex and takes much longer, so it is avoided to use it for instantiating simple models, for which the previously mentioned options are more often used.

For the proper function, the Engineering Template must include:

- References
- Input
- Parameters

The References are the basis for creating an engineering template. The model is made as a standard product with certain additional requirements that are later required when creating a template. An essential property of the elements that make up the input geometry is the need to be isolated from the rest of the product and are used only if selected as an Input by the user and defined by Parameters which are values either provided by the user or read/calculated by the model.

6 LOCAL CATALOGUES

Since the model will use standard parts and assemblies, it is necessary to compile a catalog that will contain them and that will be linked to the template. Catalogs must contain parts in all sizes and load capacities necessary to meet a given range of parameters.

To limit the necessary elements of the catalog, a test calculation was carried out for the highest load capacity and the most unfavorable load and material conditions of the Hook. According to this calculation, it is evident that the maximum Hook Number would be 80, therefore, all elements of the catalog relate to Hook number up to that number.

The first step in forming a catalog is to create a master catalog that will contain all the chapters into which individual elements will be further classified. The chapters within the catalog are as follows:

- Hooks,
- Hook carriers,
- Hook nuts,
- Bearings (both for Hooks and pulleys),
- Pulleys (standard dimensions for pulley).

7 HOOK BLOCK ENGINEERING TEMPLATE

To create a template, it is first necessary to create a parametric model of the Hook Block, which will contain geometry, parameters, and necessary elements, i.e. parts. Development of the Hook model will be divided into several stages:

- Creating input geometry and entering input parameters,
- Programming (the calculation for all components)
- Creation of skeletal geometry that will be adapted to the results of the calculation,
- Introduction of catalog components into the assembly,
- "In-context" design of other necessary components.

The first step to create a parametric model of the Hook Block, as previously stated, is to select the input geometry. An optional reference point (Optional Reference Point) will be used as the input geometry for instantiating the template into the assembly. The reference point can determine the exact position of the Hook Block, with the possibility of rotation around all three axes. The point will be set as an optional input, which will allow instantiation without selecting the input geometry, and the Hook Block will be instantiated to the origin of the global coordinate system of a particular circuit.

The skeleton model (Fig. 3) will be created as a separate 3D shape (3DShape) within the assembly. It will contain all the necessary geometry and parameters according to which the appropriate components will be selected from the catalog, i.e. new elements will be modeled.

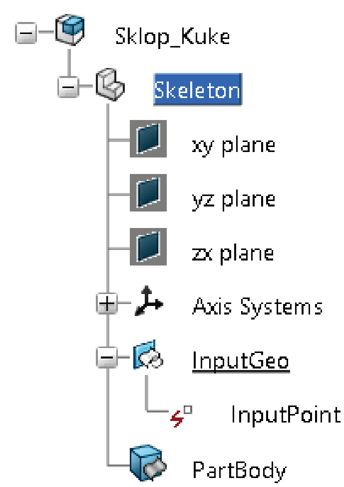

Figure 3 Feature tree with 3DShape and Input Point

The next step in the process is to enter the input parameters and other parameters that will be calculated using them and are needed to perform the calculation. All parameters are grouped within the *Knowledge Engineering Specification* module which allows the user to set the parameters to the highest level in the tree. The advantage of this configuration is that all elements within the tree will be able to use these parameters directly and refer to them. For the sake of clarity, the parameters are grouped within individual sets.

Material parameters are connected to the input parameter of the material strength class via the Design Table. For the load class and Hook material, an Excel table was created to be used as the *Resource Table* associated with the model. A resource table is a form of table that allows the loading of a series of resources, whether they are Excel spreadsheets, Word documents, etc., directly from the working server into the model. Resources in a table don't become part of the model until they're directly invoked, that is, instantiated. The advantage of using the *Resource table* is that the user can very easily put a large number of different elements at his disposal without the need to enter each element individually into the tree and then activate/deactivate them.

To choose the correct load class and corresponding safety factors it is necessary to write a code defined by the choice algorithm. For this purpose, the *Reaction function* within the *Engineering Rules* module is used, which will run the code, when there is a change in the input parameters. The full codes is shown in Fig. 4.

The code is written in ECL (*Enterprise Knowledge Language*) which is a specialized programming language designed to work in CATIA. It is based partly on the C++ programming language with some functions specific to this field of application.

```
let PG(DTSheetType)
set PG=CreateSheet("PG")

let Mat(String)
let Pog(String)
let i(integer)
let j(integer)
let row(Integer)
let col(Integer)

row=PG.RowsNb
col=PG.ColumnsNb
i=1
j=1
for i while i<=row
{
        Mat=PG.CellAsString(i,1)
        if LiftingHook_MaterialGroup==Mat
        {
                break
        }
}
for j while j<=col
{
        Pog=PG.CellAsString(0,j)
        if Load_Group==Pog
        {
                break
        }
}
cn=PG.CellAsReal(i-1,j-1)
vn=PG.CellAsReal(row-1,j-1)
```

Figure 4 Reaction for selecting powertrain factors and safety factors

With the specified factors and input parameters selected, it is possible to determine the required Hook Number. To select the Hook Number, a similar code is written (Fig. 5), which compares the calculated Hook Number with the standard numbers from the table and selects the first one larger than the calculated one.

```
let BK(DTSheetType)
set BK=CreateSheet("BK")

let i(integer)
let row(integer)
let br(real)
let kt(real)
row=BK.RowsNb
i=1
br=Max_Load/(1T*cn)
for i while i<=row
{
        kt=BK.CellAsReal(i,1)
        if br<kt
        {
                break
        }
}
Hook_Number=kt
```

Figure 5 Reaction for selecting Hook Number

With the selected Hook Number, it is possible to start making skeleton geometry (Fig. 6). The overall skeleton geometry is based on a combination of points, lines, and planes interconnected with parameters. The diameter parameters are used to determine how the geometry of the skeleton is changed using formulas and rules.

Since it is necessary to change the position of the coordinate systems by changing the catalog elements, a *Deign Table* was created that contains dimensions depending on the number of Hooks, and its change was determined using Reaction.

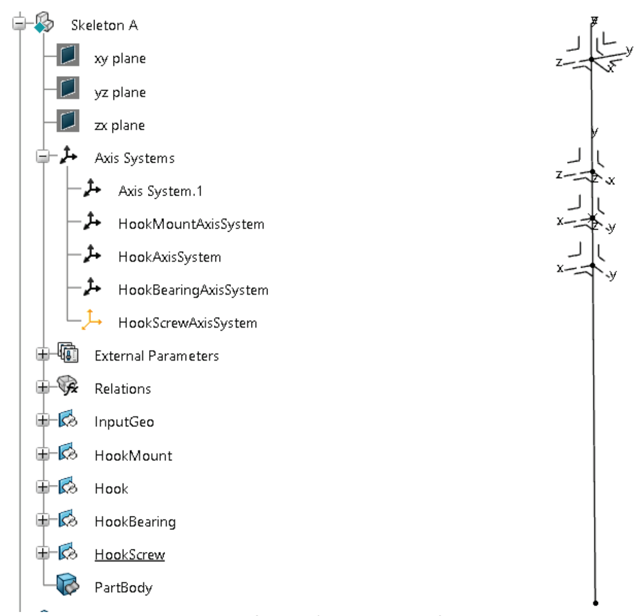

Figure 6 Positioning System for Hook Block Catalog Models

The next step is to fill in the *Resource Table* with all the catalog parts for which positioning systems have been added. Each part within the table is assigned an abbreviated name that will be used when editing the *Product Table*. With the help of additional coordinate systems, the positions of the ropes were determined. Using the *Product Table*, the number of ropes in the assembly will change according to the calculated number of Hooks. Fig. 7 shows the final Hook Block.

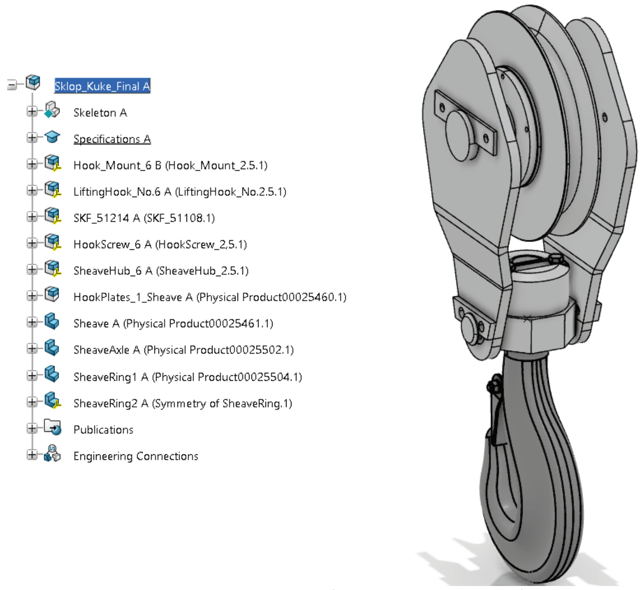

Figure 7 Hook assembly for Hook numbers up to 6

8 TEMPLATE OF TECHNICAL DOCUMENTATION

As part of the generic model of the Hook Block, it is also possible to add technical drawings of the assembly, i.e. individual components. For elements modeled as part of it, the technical documentation is created according to a standard process, and after the template is instantiated (Fig. 8), these dimensions in the drawing are automatically updated.

The biggest problem when creating a circuit drawing is during significant changes to the configuration of the assembly, where it is no longer possible to easily adjust the dimensions. One option to solve this problem could be to create a larger number of drawings for each significant configuration change and use the ECL code to activate/deactivate them as needed.

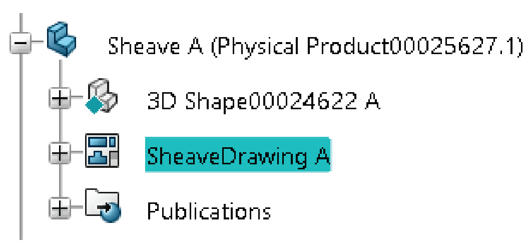

Figure 8 Thechnical Documentation added to the rope tree

Automation of the creation of technical documentation from an instantiated engineering template is still a novelty and as such has not been fully developed in the *3DExperience* software package. The principle applies to simpler assembly and workshop drawings, but for more complex products it is not possible to produce sufficiently accurate documentation that does not require intervention and corrections by the user. In addition to the above, it also requires a significant expenditure on working hours in preparation for the documentation to be of acceptable quality.

9 TEMPLATE INSTANTIATION

The created engineering template of the Hook Block can now be fully tested in the reference assembly. The *Physical Product* will be used as a reference assembly, in which a model of a simple crane and a separate *3DShape* have been added (Fig. 9). In preparation for instantiation in *3DShape*, it is necessary to add the point at which the template is to be instantiated, otherwise it will be instantiated at the origin of the main assembly.

After the parametric assembly of the Hook has been made, it is possible to make an engineering template from it. To instantiate the template itself, it is necessary to select the *Engineering Template Instantiation option* in the *Assembly* module (Fig. 10).

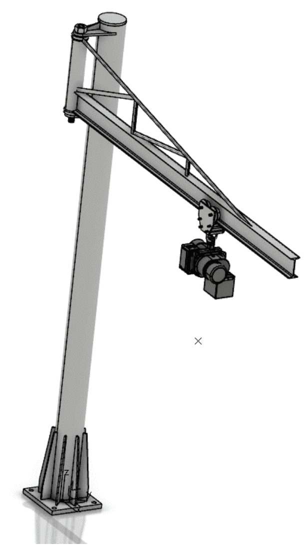

Figure 9 Physical Product with Template Instantiation Reference

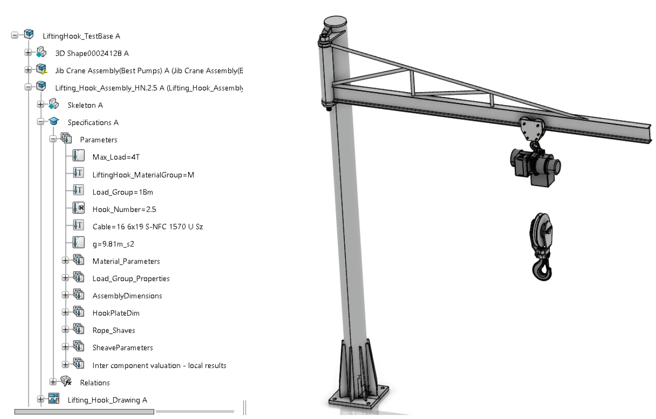

Figure 10 Physical product with added developed Hook Block

It is necessary to select the engineering template that is required to be instantiated which is possible by selecting the template directly or by selecting the template in the catalog.

Finally, by clicking on the OK button, the template is instantiated in the assembly. It is also possible to instantiate a template multiple times in a row by selecting the Repeat option. Instantiating a template creates new references for all elements of the assembly. This makes it possible to make changes to the instantiated assembly without changing the elements of the original model.

By entering the parameters of the assembly, the given input parameters, the calculated number of Hooks, and the required dimensions of the rope are visible. The parameters can also be subsequently changed as needed, which will result in the adaptation of the model itself.

10 CONCLUSION

In this paper, the process of creating an engineering template of the Hook assembly based on the parametrically designed model in the *3DExperience* software package is described. For the creation of the parametric model, an algorithm for calculation, design, and sizing of the Hook Block is defined.

The use of parametrically designed models and engineering templates can significantly speed up the process of making products that use a larger number of standard elements or elements for which there are predetermined calculations. The use of parametric models also accelerates the process of modification of existing models due to the possibility of modifying the parameters, according to which the adaptation of the rest of the model is made. The creation of the models themselves requires more time and higher proficiency in a certain software package.

Parametric modeling and the use of engineering templates represent a higher step of 3D modeling and product design that is increasingly applied in modern industry and knowledge of their principles will become an important skill for many engineers.

11 REFERENCES

[1] Jinggao, L., Byung, C. K. & Soonhung, H. (2012). Parametric exchange of round shapes between a mechanical CAD system and a ship CAD system. *Computer-Aided Design, 44*(2), 154-161. https://doi.org/10.1016/j.cad.2011.08.003

[2] Qiang, Z., Yingcai, W., Zhenyu, L., Weiwei, X. & Shuming, G. (2024). Intelligent CAD 2.0. *Visual Informatics, 8*(4), 1-12. https://doi.org/10.1016/j.visinf.2024.10.001

[3] Hunde, B. R. & Woldeyohannes, A. D. (2022). Future prospects of computer-aided design (CAD) – A review from the perspective of artificial intelligence (AI), extended reality, and 3D printing. *Results in Engineering, 14*, 100478. https://doi.org/10.1016/j.rineng.2022.100478

[4] Jayakiran, E. R. & Rangadu, V. P. (2018). Development of knowledge based parametric CAD modeling system for spur gear: An approach. *Alexandria Engineering Journal, 57*(4), 3139-3149. https://doi.org/10.1016/j.aej.2018.07.010

[5] Raikar, P. P., Anand, N., Pini, M. & De Servi, C. (2025). Concurrent optimization of multiple heat transfer surfaces using adjoint-based optimization with a CAD-based parametrization. *International Journal of Heat and Mass Transfer, 236*(1), 126230. https://doi.org/10.1016/j.ijheatmasstransfer.2024.126230

[6] Geren, N., Akçalı, O. O. & Bayramoglu. M. (2017). Parametric design of automotive ball joint based on variable design methodology using knowledge and feature-based computer assisted 3D modelling. *Engineering Applications of Artificial Intelligence, 66*, 87-103. https://doi.org/10.1016/j.engappai.2017.08.011

[7] Ščap, D. (1990). *Prenosila i dizala*. Drugo izdanje, Sveučilište u Zagrebu. (in Croatian)

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Superposition Methods for Topology Optimization for Non-Concurrent Loads

Daniel Miler, Matija Hoić*

Abstract: Problems with non-concurrent loads with variable load directions are often encountered in engineering. While dynamic topology optimization more realistically solves such problems, it is also much more computationally expensive and requires complex mathematical formulations and solvers. Hence, in this paper, we compared the performances of three superposition methods for fusing topologies obtained for various load directions. The top88 algorithm was used to generate 91 initial topologies using MATLAB, which were then joined via the superimposition method, weighted-density parameter, and the revolutionary superposition layout method. The performances of superposed topologies were then analysed by calculating their compliances for various load conditions via the finite element method also using MATLAB. The results have shown that the superimposition method and the weighted-density parameter method yield rather similar results. Both methods provided structures with lower total compliances compared to the revolutionary superposition layout method, making them more suitable for problems where stiffness is paramount.

Keywords: non-concurrent loads; superposition methods; topology optimization; variable load direction

1 INTRODUCTION

Topology optimization is a method enabling optimal distribution of material with respect to a given criterion, most often compliance of the structure [1]. In a general case, the domain within which the material is distributed is defined, along with support positions and load properties (position, direction, magnitude), and material volume fraction [2]. The problem is formulated in a way that it is necessary to find the material distribution that minimizes the compliance of the structure subjected to volume constraint and additional constraints (filled or void elements, supports) [3].

Many algorithms for topology optimization are available as open source and are most often based on the SIMP approach (solid isotropic material with penalization). SIMP is a density-based approach that transforms the discrete to continuous variables, reducing the problem complexity [4]. The majority of methods for topology optimization are still focused on static optimization in which the domain and loads are static. However, dynamic topology optimization, which considers time-dependent loads and dynamic responses, is gaining significance. It is particularly attractive in fields such as aerospace, automotive, and seismic engineering, where structures are subjected to dynamic forces [5].

Dynamic loading conditions are also encountered when optimizing mechanisms that are subjected to non-concurrent loads with variable directions, such as slider-crank systems or manipulator links [6]. While there were attempts to solve such problems by considering only the static load in the worst-case position [7], such an approach results in limited design quality. Hence, methods accounting for multiple mechanism positions were developed and are mostly based on superposing the results of multiple static topology optimization processes [8–10].

Srinivas and Javed [8, 9] proposed the superimposition method to improve the structural performance of manipulators subjected to varying operational conditions. The method joins topologies optimal for different load cases into a unified topology [9]. The same authors proposed the weighted-density parameter approach which fuses multiple optimized topologies based on the element-wise sensitivity and volume fraction [11]. Element sensitivities are measured by summing the density parameters of each optimal topology for all the elements. Finally, Alkalla et al. [10] proposed the revolutionary superposition layout (RSL) method which combines multiple independent optimal designs to generate a topology that will meet the performance criteria of all loads.

In this article, the authors compared the available approaches to superposition of topology-optimized structures subjected to variable load directions. Firstly, the optimal topologies for each step of the observed case problem, in which the load direction was varied, were obtained via top88 [12]. Next, topologies were joined using three available approaches – the superimposition method [9]. weighted-density parameter [11], and the revolutionary superposition layout (RSL) [10]. The compliances and volume fractions were calculated for each of the outputs and were compared.

While previous studies have explored individual methods, a direct comparative analysis of their performance and structural effectiveness was lacking. By implementing these methods on a benchmark problem and evaluating their compliance results, this work offers valuable insights into their relative advantages and limitations. The findings contribute to the broader understanding of superposition-based topology optimization and provide practical guidance for selecting appropriate methods based on structural and computational considerations.

2 CASE STUDY

The example structure used in a case study is a structure supported on the left side (encastre, all degrees of freedom fixed) and subjected to a concentrated load F = 100 on the right side (no unit; see Section 3.4). The load is applied in the middle of the right domain edge and has variable direction. The direction was varied from 0° (horizontal load action) to 90° (vertical). Topology optimizations were carried out at load increments of 1° which resulted in a total of 91 optimized geometries. The domain size and shape, applied supports, and load are shown in Fig. 1.

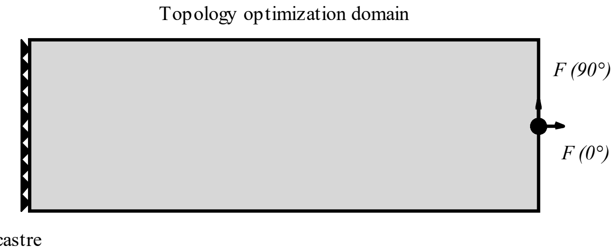


Figure 1 Example problem – domain size, support locations, and load positions

The domain size was 300 × 100 elements, and the topology optimization was carried out using the top88 algorithm [12]. The algorithm settings were as follows – volume fraction was 0.3, penalty factor was 3, as well as the minimum filter radius $r_{\min}$. The density-based filtering method was used with a modified SIMP approach. The move factor was 0.2 and the maximum number of iterations for each load position was set to 100. Additionally, the Poisson ratio of the selected material was taken as 0.3.

The optimal topologies were obtained for all 91 cases and were saved in one 3D matrix with a size of 91 × 100 × 300. Said 3D matrix was denoted as *distributions* and was used as input in the following steps.

3 METHOD

Four methods for superposition of topology-optimized structures for non-concurrent loads were compared (methods are briefly outlined in sections 3.1 to 3.3). To do so, it was first necessary to obtain optimal topologies for the observed case found according to the process outlined in Section 2. The matrix *distributions* was used as input for all of the compared methods.

Since methods for superpositioning topologies generally result in greater volume densities compared to the base topologies, their volume fractions were limited to volume fraction v_{f} = 0.5. For this reason, aiming to facilitate the comparison between the results of superposed topologies and topologies for specific loads, optimal topologies were also obtained using v_{f} = 0.5 for load angles 0°, 30°, 60°, and 90°.

3.1 Superimposition Method

The method outlined in [8] was used to implement the superimposition method. First, optimal topologies contained in the matrix *distribution* were loaded and *superimposition* MATLAB function was carried out. The function summed the densities of all the elements along the first dimension (number of topologies).

After the densities of elements across topologies were summed up, normalization to a scale [0, 1] was carried out to ensure that the realistic material density was used. Next, the target threshold needed to achieve the previously selected volume fraction was calculated. The final design was obtained after eliminating all the elements below the target threshold. The mathematical model for the superimposition method used in this paper is given as [8]:

$$\begin{aligned} \boldsymbol{T}_{\mathrm{sup}} &= \sum_{k=1}^{91} \boldsymbol{T}_k, \\ \boldsymbol{T}_{\mathrm{nor}} &= \frac{1}{91 \cdot v_{\mathrm{f}}} \boldsymbol{T}_{\mathrm{sup}}, \\ \boldsymbol{T}_{\mathrm{RP}} &= \left[\boldsymbol{T}_{\mathrm{nor}}\right]^{\tau}, \end{aligned} \tag{1}$$

where $\boldsymbol{T}_k$ is the matrix containing element densities of k^{th} optimal topology, k is the number of topologies (k = 91 in this paper), $\boldsymbol{T}_{\mathrm{sup}}$ is the matrix containing $\boldsymbol{T}_{\mathrm{nor}}$ is the matrix containing the normalized topologies,

It should be noted that the additional image processing was omitted in this paper due to space constraints.

3.2 Weighted-Density Parameter

The weighted density method was outlined in [11] and the associated mathematical model was given in Eq. (2). To carry out the weighted-density parameter approach, it is first necessary to determine the weight number of each element W_{eij}. Its value is calculated by summing the density values of specific elements for all optimal topologies x_{eij}, where e is the topology and i and j represent the number of rows and columns, respectively. The numerical factor T is calculated based on the number of topologies that are being superposed and the volume fraction. Finally, binary density values are obtained after comparing the element weights; these larger than 0 were taken as material.

$$\begin{aligned} W_{eij} &= \frac{\sum_{k=1}^{91} T_{kij} - T}{T}, \\ T &= 91 \cdot \left(1 - v_{\mathrm{f}}\right), \\ x_{eij} &= \begin{cases} 1 & W_{eij} \geq 0 \\ 0 & W_{eij} < 0 \end{cases} \\ i &= 1, 2, ..., 100; j = 1, 2, ..., 300. \end{aligned} \tag{2}$$

3.3 Revolutionary Superposition Layout

The RSL method [10] is a systematic approach for optimizing structures subjected to non-concurrent multi-load conditions. As was the case in previous two methods, the optimal topology is first determined for individual load cases separately, using any topology optimization algorithm, and the final design is obtained by combining them.

Since the method was intended to be used when there are up to three non-concurrent loads, three cases were used to create superposed topology. These were structures obtained for 0° ($\boldsymbol{D}_0$), 45° ($\boldsymbol{D}_{45}$), and 90° ($\boldsymbol{D}_{90}$) load angles. The mathematical model is given in [10] as:

$$\boldsymbol{D}_{\mathrm{opt}} = \boldsymbol{D}_0 \cup \boldsymbol{D}_{45} \cup \boldsymbol{D}_{90} = \sum_{i=1}^{n} \max_{j=1}^{m} \left\{x_{ij}\right\}, \tag{3}$$

where $\boldsymbol{D}_{\mathrm{opt}}$ is the final resultant optimum design, $m = 3$ is the number of concurrent loads being observed, and x_{ij} is the highest relative density of element i at any of load cases j.

The method takes the maximum density across optimal topologies for each element. Next, densities were normalized to the interval [0, 1] and thresholding was carried out to ensure that the volume fraction was 0.5.

3.4 Finite Element Method

The finite element method (FEM) was used to analyse the obtained superposed topologies. The FEM analysis used in this paper was implemented in MATLAB. Each finite element was taken as a linear quadrilateral element. Young moduli of elements with material were taken as $E = 1$, while empty elements were assigned value $E_{\min} = 10^{-9}$ to avoid the stiffness matrix from becoming singular. Since no units were assigned to Young moduli, no unit was applied to the concentrated load F. The Poisson's ratio was taken as 0.3 and the material was assumed to be homogenous and isotropic.

The finite element method carried out in this paper was based on the implementation provided in [12]. The domain was comprised of 30000 elements with a total of 60802 degrees of freedom. The applied boundary conditions and loads were identical to those presented in Section 2.

4 RESULTS AND DISCUSSION

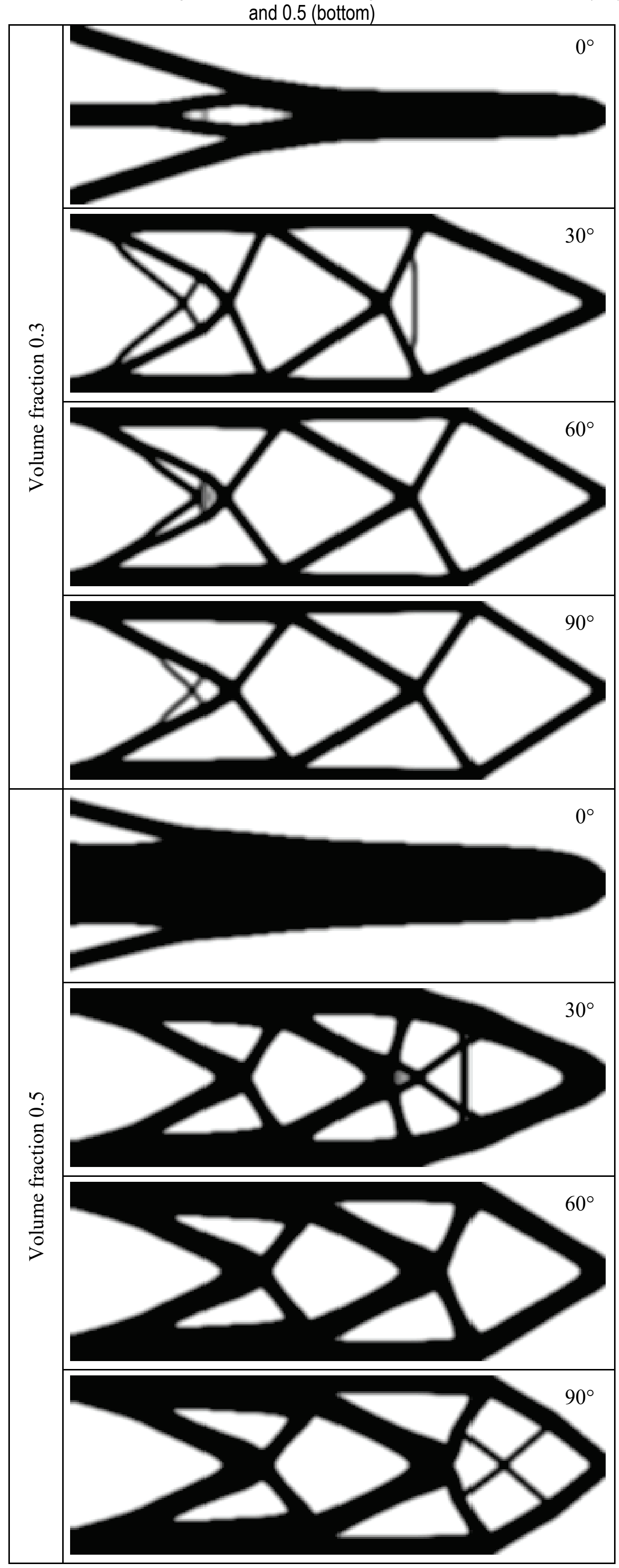
A total of 91 optimal topologies were obtained for the considered case. The optimization was carried out using MATLAB 2010 running on a PC with Intel i5-8500 CPU at 3.00 GHz and 32 GB of RAM. For illustration purposes, four optimal topologies obtained for load angles of 0°, 30°, 60°, and 90° and volume fraction $v_{\mathrm{f}} = 0.3$ are shown in Tab. 1.

The approximate computational time needed to carry out one optimization was determined using the tic and toc functions native to MATLAB. The time needed to optimize one topology was 44.16 to 49.73 s. On the other hand, carrying out the FEM simulation takes approx. 0.68 s. Lastly, the superposition of optimal topologies was practically instantaneous, so computational times were not calculated.

As shown in Tab. 1, regardless of the volume fraction, solutions obtained for lower angle loads tend to have lower distances between the normal line and the material placement compared to those obtained for larger angles. Such material distribution is more favourable with respect to compression and tension. On the other hand, taller designs fare better when subjected to bending stresses.

When comparing the effects of the volume fraction on the material distributions, the similarities are clear. As the load action angle increases, so does the amount of material placed adjacent to the top and bottom domain edges. The solutions obtained for the same load angle have rather similar outer contours.

Table 1 Optimal topologies obtained for load angles and volume fraction 0.3 (top) and 0.5 (bottom)



It was also observed that the compliance starkly increased as the load application angle was increased, i.e., depending on the type of loading. Under bending (90° load angle), compliance is primarily governed by the flexural stiffness, which depends on the moment of inertia and elastic modulus. When subjected to pure tension (0° angle), the compliance is dictated by axial stiffness, favouring a direct load-carrying path with material distributed along the force direction. Consequently, as observed in the results, topology optimization for bending results in truss-like or beam-reinforced structures, whereas tension-driven optimization produces streamlined, load-aligned designs. For cases where both bending and tension occur, the optimized topology integrates these characteristics, balancing axial stiffness with flexural resistance to achieve an efficient load-bearing structure.

4.1 Superposed Solutions

Optimal topologies obtained for load angles from 0° to 90° and volume fraction 0.3 were superposed using the three above-listed methods. The resulting material distributions are shown in Tab. 2

As can be seen from Tab. 2, superposed topologies obtained using the superimposition method and the weighted-density parameter approach are practically identical. This is due to their approach, which relies on applying a threshold value to the normalized sum of superposed topologies. Both topologies are rather similar to that obtained for load at a 60° angle at volume fraction 0.5 (shown in Table 1), with minor differences, with the key difference being additional holes near the base.

On the other hand, the structure obtained using the revolutionary superposition layout is rather different compared to the original topologies. It also utilizes thin streaks of material, which makes the piece more complex for the manufacturer. Additionally, there are small areas with no material located within the solid domain areas, possibly implying the existence of a checkerboard problem.

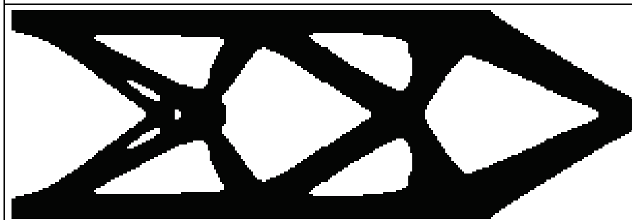
Next, the compliances of the three superposed topologies were compared to compliances of original topology optimized structures at angles 0°, 30°, 60°, and 90° obtained for volume fractions 0.3 and 0.5. The compliances were calculated using the finite element method outlined in Section 3.4. and the results are shown in Tab. 3. The naming convention for the original topology-optimized structures indicates the load angle used during optimization and the corresponding volume fraction. For instance, the structure labeled "Angle 30°, $v_f = 0.3$" was optimized for a load applied at 30° with a volume fraction of 0.3.

As expected, compliances between the superimposition method and the weighted-density parameter approach are identical. When compared to the results of the RSL method, it can be seen that the RSL method yields better results when the load is applied at angles of 0° and 15°. As the load angle increases, the superimposition method and the weighted-density parameter approach have better results.

However, unexpected results were obtained as the structure obtained for 30° angle and volume fraction 0.5 gives better results than all the superposed topologies, except for RSL at 0° angle. Such results imply that there is no need for superposition, as one of the original topologies is shown to have better results. This might be significant since, even though the superposition itself has a low computational cost, generating the necessary topologies is very resource-intensive. Similar results were obtained for the 60° angle structure ($v_f = 0.5$), which had lower compliances than all the superposed topologies at angles of 30° and over.

Table 2 Superposed topologies obtained using three different methods

Superimposition method



Weighted-density parameter

Revolutionary superposition layout

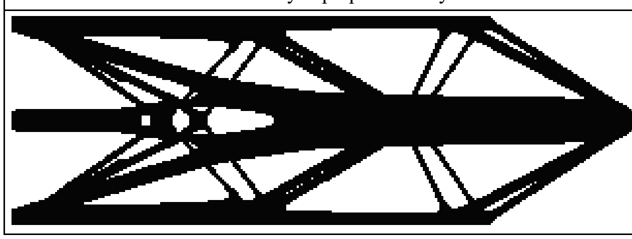


Table 3 Compliances of structures depending on the load angle applied to them (value divided by 10^5 for formatting reasons)

The method used to obtain the structure	Load angle						
	0°	15°	30°	45°	60°	75°	90°
Superimposition	1.37	2.59	5.91	10.5	15	18.3	19.5
Weighted-density	1.37	2.59	5.92	10.5	15	18.3	19.5
RSL	1.04	2.54	6.62	12.2	17.8	21.8	23.3
Angle 0°, $v_f = 0.3$	1.41	15.4	53.5	106	158	196	210
Angle 30°, $v_f = 0.3$	2.6	4.53	9.78	17	24.1	29.4	31.3
Angle 60°, $v_f = 0.3$	3.7	5.47	10.3	16.9	23.6	28.4	30.2
Angle 90°, $v_f = 0.3$	4.38	6.1	10.8	17.2	23.6	28.3	30
Angle 0°, $v_f = 0.5$	0.896	5.01	16.3	31.6	47	58.2	62.3
Angle 30°, $v_f = 0.5$	1.25	2.4	5.53	9.82	14.1	17.2	18.4
Angle 60°, $v_f = 0.5$	1.81	2.89	5.85	9.89	13.9	16.9	18
Angle 90°, $v_f = 0.5$	2.36	3.42	6.32	10.3	14.2	17.1	18.2

4.2 Limitations

The limitations of the study at hand should be addressed. The study at hand was also focused on the 2D space, which is not true for most engineering problems. While all the methods can be easily extended to 3D space, doing so would significantly increase the computational cost. Increasing the dimensionality to 3D space would introduce an additional degree of freedom to each node, greatly expanding the global stiffness matrix. Since topology optimization is an iterative process and since it is necessary to generate a large number of topologies for different load angles, it might be necessary to either reduce the domain size or use parallel computing functions.

Moreover, the obtained results are only illustrative, as the more thorough comparison warrants using multiple examples to confirm the robustness of the findings. Additional examples should be introduced with various types of loads domain sizes and shapes. Finally, the application of various filters on the superposed results was not considered in this paper. Introducing the use of filters will result in increased manufacturability of specimens.

5 CONCLUSION

This study compared three superposition methods—Superimposition, Weighted-Density Parameter, and Revolutionary Superposition Layout (RSL)—for topology optimization under non-concurrent loads with variable load directions. The methodology involved generating optimal topologies for 91 different load angles using the top88 algorithm and subsequently combining them using the three superposition approaches. The performance of the resulting structures was evaluated in terms of compliance under various loading conditions using the finite element method.

The results demonstrated that the Superimposition and Weighted-Density Parameter methods produce nearly identical topologies, both achieving lower compliance values compared to the RSL method in most loading scenarios. However, the RSL approach exhibited superior stiffness when the load direction was aligned with the structure's primary load-carrying path (e.g., at 0°). Interestingly, the optimal topology for a single load angle of 30° and volume fraction of 0.5 outperformed all superposed topologies in several cases, suggesting that worst-case load conditions might be a viable alternative to superposition in some applications.

These findings indicate that while superposition methods provide a computationally efficient alternative to full dynamic topology optimization, their effectiveness depends on the specific loading conditions. Furthermore, the study highlights the need for further research into hybrid approaches that incorporate adaptive volume constraints and filtering techniques to refine superposed topologies.

Future work will focus on extending these methods to three-dimensional structures and applying them in multi-body system optimization, where topology changes due to motion and load variation are more complex. Additionally, investigating the integration of superposition methods with gradient-based optimization strategies could enhance their adaptability and computational efficiency in more complex engineering problems.

6 REFERENCES

[1] Bendsøe, M.P., Sigmund, O. (2003). *Topology Optimization: Theory, Methods and Applications* (2nd ed), Berlin, Springer. https://doi.org/10.1007/978-3-662-05086-6

[2] Sigmund, O. (2001). A 99 line topology optimization code written in Matlab. *Structural and Multidisciplinary Optimization, 21*, 120-127. https://doi.org/10.1007/s001580050176

[3] Sigmund, O., & Maute, K. (2013). Topology optimization approaches: A comparative review. *Structural and Multidisciplinary Optimization, 48*, 1031-1055. https://doi.org/10.1007/s00158-013-0978-6

[4] Deaton, J. D., & Grandhi, R.V. (2014). A survey of structural and multidisciplinary continuum topology optimization: Post 2000. *Structural and Multidisciplinary Optimization,* 49, 1-38. https://doi.org/10.1007/s00158-013-0956-z

[5] Sun, J., & Hu, H. (2024). Dynamic topology optimization of flexible multibody systems. *Nonlinear Dynamics, 112*, 11711-11743. https://doi.org/10.1007/s11071-024-09619-3

[6] Ghandriz, T., Führer, C., & Elmqvist, H. (2017). Structural topology optimization of multibody systems. *Multibody System Dynamics,* 39, 135-148. https://doi.org/10.1007/s11044-016-9542-7

[7] Lv, X., Yang, Y., Zeng, W., & Xu, D. (2019). Lightweight Design of Six-dof Tandem Manipulator Based on Additive Manufacturing Technology. *IOP Conference Series: Materials Science and Engineering, 612*(3). https://doi.org/10.1088/1757-899X/612/3/032145

[8] Srinivas, G. L., & Javed, A. (2021). A novel method to synthesize a single topology for dynamically loaded members. *Journal of Mechanical Science and Technology, 35*, 1549-1557. https://doi.org/10.1007/s12206-021-0319-4

[9] Srinivas, G. L., & Javed, A. (2020). Topology optimization of rigid-links for industrial manipulator considering dynamic loading conditions. *Mechanism and Machine Theory, 153*, 103979. https://doi.org/10.1016/j.mechmachtheory.2020.103979

[10] Alkalla, M. G., Helal, M., & Fouly, A. (2021). Revolutionary superposition layout method for topology optimization of nonconcurrent multiload models: Connecting-rod case study. *International Journal for Numerical Methods in Engineering*, 122(5), 1378-1400. https://doi.org/10.1002/nme.6582

[11] Srinivas, G. L., & Javed, A. (2021). Synthesis and performance evaluation of manipulator-link using improved weighted density matrix approach with topology optimization method. *Engineering Science and Technology, an International Journal, 24*, 1239-1252. https://doi.org/10.1016/j.jestch.2021.02.010

[12] Andreassen, E., Clausen, A., Schevenels, M., Lazarov, B. S., & Sigmund, O. (2011). Efficient topology optimization in MATLAB using 88 lines of code. *Structural and Multidisciplinary Optimization, 43*, 1-16. https://doi.org/10.1007/s00158-010-0594-7

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Numerical Optimisation of Mould and Injection Moulding Process: Case Study

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Abstract: The paper presents the optimisation of mould for injection moulding as well as injection moulding process parameters using numerical computer simulation in the Moldex3D software package. The optimisation process will be applied to a specific moulded part – branching terminal block – and an already manufactured mould. The paper includes evaluation of the existing mould for injection moulding designed and manufactured without application of numerical simulation of injection moulding process. According to the shortcomings found out in evaluation process, by application of numerical simulation of injection moulding process, the optimisation of the mould design was conducted in several stages to achieve as optimal as possible moulded part quality and injection moulding process parameters without dramatic changes in already manufactured mould.

Keywords: injection moulding; Moldex3D; mould for injection moulding; numerical computer simulation; optimisation

1 INTRODUCTION

Today with the injection moulding process, moulded parts of very complex geometries are made from polymer materials with very different properties. The market puts high demands on the quality of such products, and at the same time demands for a shorter cycle of injection moulding, and lower prices of moulds and moulded parts. To meet those requirements, computer simulation using CAE (*Computer Aided Engineering*) software is necessary [1, 2]. Computer simulation can be powerful tool for prediction certain defects and problems related to the mould and moulded part design, as well as injection moulding parameters [1, 3]. Observed defects and problems can be eliminated in the early stages of development and design. This is much more economical and efficient compared to solving them when the mould is already made [1, 2]. Computer simulation also can be applied to optimise the mould design, the quality of the moulded part and injection moulding process parameters [4, 5]. The paper presents a case study of optimisation of already made mould for polymer product - branching terminal block [6]. By applying a computer simulation using the Moldex3D software package on the existing condition, an insight into the causes of errors in the mould design was obtained, and optimisation steps are evaluated.

2 ANALYSIS OF EXISTING SYSTEM FOR INJECTION MOULDING

2.1 Moulded Part and Mould [6]

Branching terminal block is used for breaking the insulation of insulated conductors in a bundle as well as for connecting the cores of the house connection cable and public lighting. The branching terminal block assembly consists of 7 basic elements, and the subject of the optimisation in this paper is the upper and lower part of the clamp housing made by injection moulding.

The material of the clamp housing is polyamide PA6-GF30 reinforced with 30% glass fibres, resistant to UV (*Ultraviolet*) radiation and weather conditions. The approximate dimensions of the upper part of the clamp housing are 57 × 55 × 35 mm, and the lower part of the housing is 50 × 50 × 25 mm. Fig. 1 shows the CAD (*Computer Aided Design*) models of the upper and lower parts of the clamp housing.

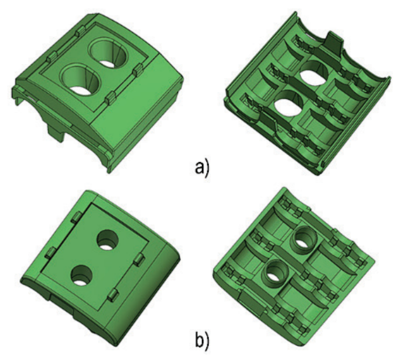

Figure 1 Branching terminal block housing: a) upper part, b) lower part [6]

Already made mould is a two-cavity mould. One mould cavity is used for moulding the upper part, and the other for moulding the lower part of the branching terminal block. Mould cavities are made using the dies in a fixed mould plate, and cores in a movable mould plate. Fig. 2 shows a movable and a fixed mould plate.

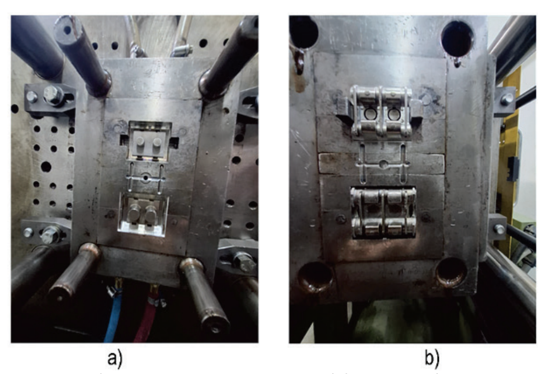

Figure 2 Mould for branching terminal block: a) fixed side, b) movable side [6]

The runner system (Fig. 3) is designed as a cold runner system with a nozzle height of 60 mm and an initial diameter of 3 mm, a main runner channels with a circular cross-section and 5 mm in diameter and four manifold channels with a circular cross-section and 4 mm in diameter. Each mould cavity is connected to runner system by means of the tunnel gates. The tunnel gate is made in a fixed moulding plate at an angle of 35° in relation to the parting plane, with an end diameter of 1 mm and a length of 3,2 mm.

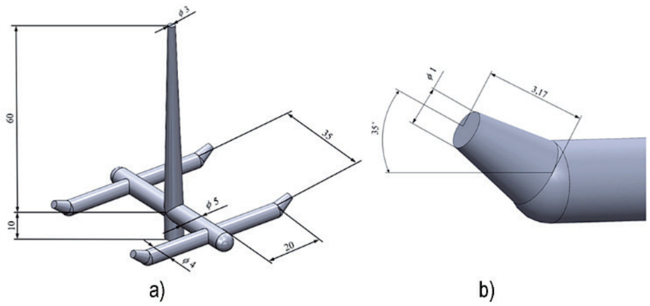

Figure 3 Mould runner system: a) runner system elements, b) tunnel gate [6]

The resulting tempering system (Fig. 4) consists of two cooling channels of circular cross-section with a diameter of 6 mm, spaced 170 mm apart, on each of the moulding plates. The cooling channels are not connected to each other, i.e. each of them has a separate inlet and outlet of the tempering medium outside the mould.

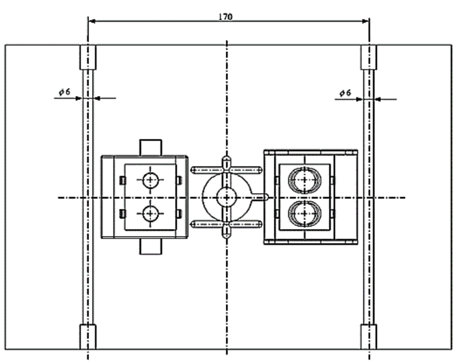

Figure 4 Mould cooling channels (movable mould plate) [6]

2.2 Definition of Simulation Model

For the computer simulation of the injection moulding process, the software Moldex3D was used. When applying computer simulation, the first step is to define the simulation model and generate a finite elements mesh on all simulation model elements [7]: moulded parts, runner system, cooling channels and mould plates (Fig. 5).

The next step is to define the moulded part material selected from the database of the Moldex3D – BASF Ultramid B3EG6. In the next step, within the Process Wizard module it is necessary to define the basic parameters of the injection moulding process: select the type of injection moulding machine for simulation, define the parameters of the filling phase and the packing pressure, and define the parameters of the cooling phase. Fig. 6 shows the menu for determining the parameters of the cooling phase.

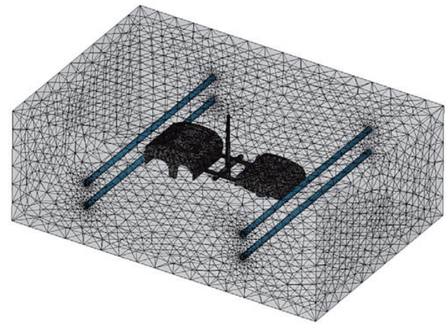

Figure 5 Simulation model with finite elements mesh [6]

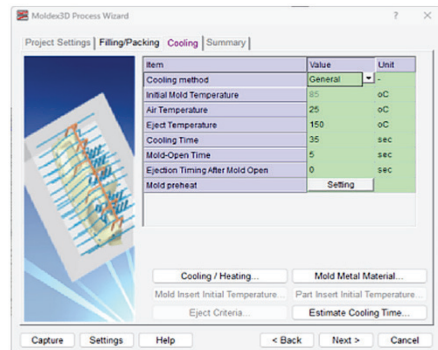

Figure 6 Process Wizard – cooling phase parameters definition [6]

2.3 Main Results of Injection Moulding Simulation [6]

Analysing the results of the previously described computer simulation, several problematic phenomena were observed during the injection moulding cycle, namely:

- uneven mould cavities filling
- appearance of air pockets
- inefficient cooling channel configuration
- moulded part warpage.

Since the existing mould consists of two mould cavities that are used to shape two different moulded parts, and which are connected by the same configuration of the runner system, it is expected that there will be uneven filling of the mould cavities. Fig. 7 shows this problem during the injection phase at the point of switching to packing pressure.

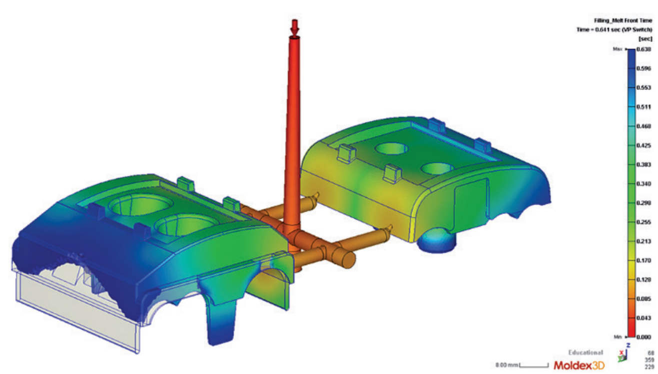

Figure 7 Uneven filling of mould cavities [6]

At the Fig. 7, it can be clearly seen that the mould cavity for the lower part of the housing is completely filled with polymer melt, while this is not the case with the mould cavity for the upper part of the housing. The unfilled part of the mould cavity will be filled with melt during the packing pressure phase. This will cause uneven cooling times of the moulded parts, i.e. while the unfilled part will be filled by the melt, the remaining parts will already begin to cool down. The goal is that at the end of the injection phase, the mould cavities are uniformly filled with polymer melt above 90 % in volume.

The appearance of air pockets occurs due to an inadequately implemented system for venting the mould cavities. Air remains trapped inside the mould cavities after mould closing, which is why the melt fails to completely fill the mould cavity. In addition to this phenomenon, there is a possibility of creating burns on the moulded parts in the form of black dots due to overheated air that remains trapped inside the mould cavity. The venting system of the existing mould is very poor, and the result is the presence of the black spots that on the mould plates, caused by the gasification of the polymer material.

Computer simulation allows the determination of the potential places of air pockets, which are shown in Fig. 8 for the existing mould.

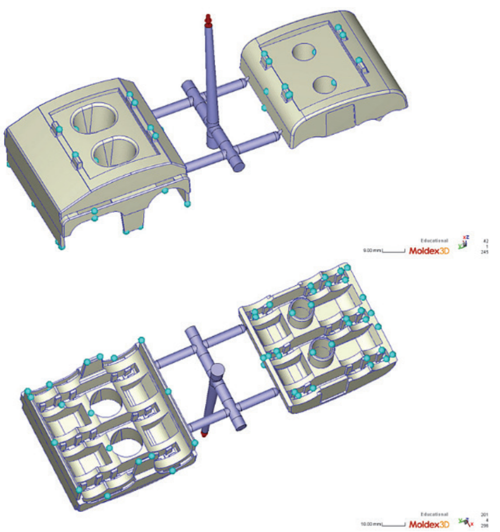

Figure 8 Air pockets - simulation results [6]

The configuration of the cooling channel described in chapter 2.1 is inefficient, and it should be kept in mind that the recommended temperature of the mould cavity wall is 85 °C (for specific polymer material), which is quite a high temperature. Therefore the removal of heat from the moulded parts is very slow and inefficient. The obtained results related to the efficiency of the applied cooling channels are shown in Fig. 9 (max. efficiency – 12,9 %).

Additional problem that needs to be eliminated during cooling phase is the reduction of rather large percentage of melt remained at the end of the cooling phase of injection moulding cycle. The current melt percentage is 3,5 % and is shown in Fig. 10.

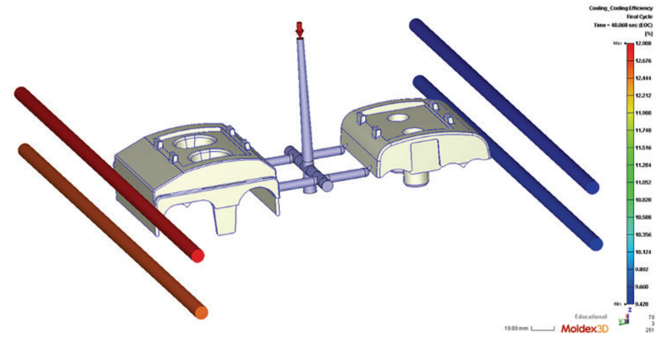

Figure 9 Cooling channels efficiency [6]

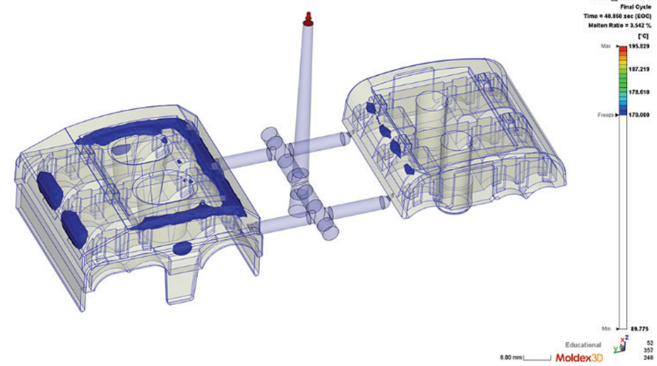

Figure 10 Percentage of unsolidified melt at the end of cooling phase [6]

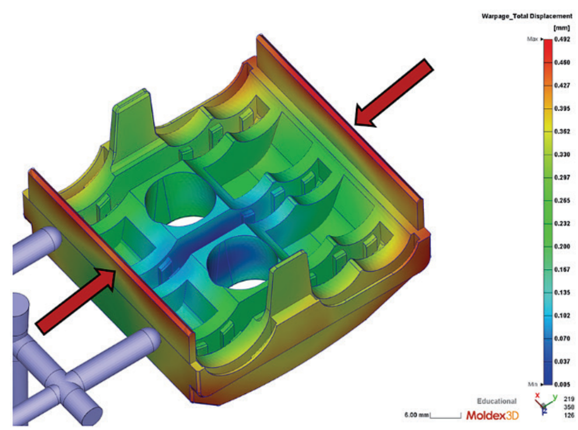

Figure 11 Warpage of the moulded upper part - simulation [6]

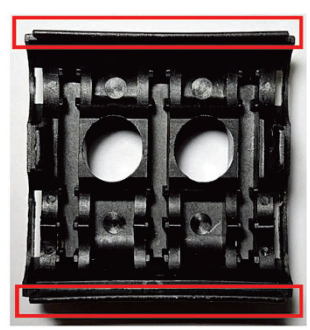

Figure 12 Warpage of the moulded part - real upper part [6]

The remaining of the melt at the end of the cooling phase causes increased warpage of the moulded part after ejection from the mould, because in these zones it was not possible to reach the temperature of shape stability. Figs. 11 and 12 show the results of the simulation of warpage of the moulded part and the actual moulded part deformation.

3 OPTIMISATION OF THE EXISTING MOULD FOR INJECTION MOULDING [6]

Based on the observed phenomena, optimisation was carried out in several steps, namely:

- optimisation of the mould runner system
- optimisation of the mould cooling system
- optimisation of the mould cavity venting system.

3.1 Optimisation of the Mould Runner System [6]

The goal of this optimisation step is to balance the filling of both mould cavities. As the optimisation is carried out on an already made mould, there are certain limitations in the optimisation possibilities. Therefore, the segments of the runner system that delivers polymer melt to the cavity for housing upper part are increased.

When optimising that part of the runner system, the dimensions of the runner channels were kept at the existing dimensions (4 mm diameter), while the final diameter of the gate was increased from 1,0 mm to 1,3 mm. The results of this optimisation step are shown in Fig. 13.

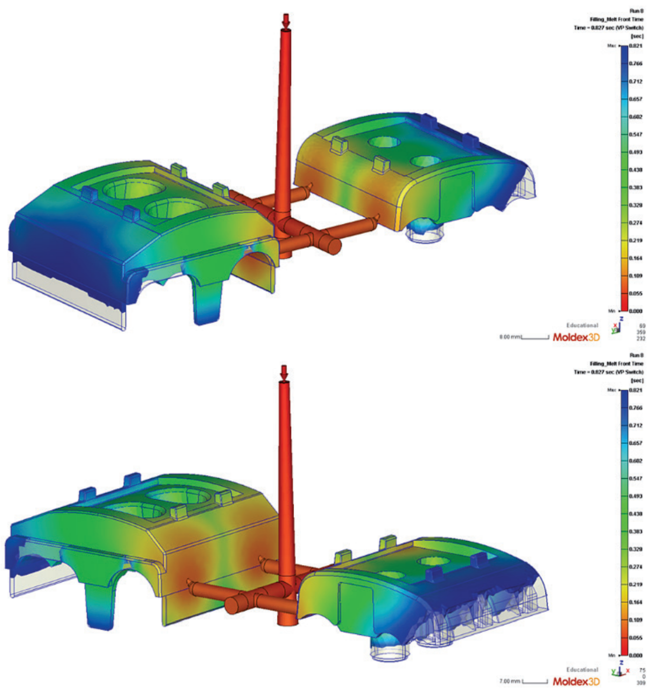

Figure 13 Results of optimisation of mould runner system [6]

Fig. 13 shows a more uniform filling of both mould cavities compared to the initial state. It can be concluded that more than 90 % filling of both mould cavities is achieved at the point of switching to packing pressure, which was the goal of this optimisation phase.

3.2 Optimisation of the Mould Tempering System [6]

Based on the existing cooling channels, it was assumed that increasing the channel diameter would not be enough, i.e. that adding new cooling channels also have to be considered. The first step was to define a new layout of cooling channels. Adding new cooling channels to the movable mould plate is not feasible due to the collision with ejector locations, so the only option left is to add cooling channels to the fixed mould plate. Fig. 14 shows the layout of additional cooling channels.

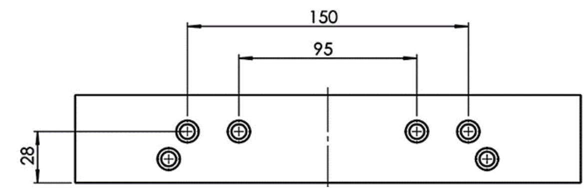

Figure 14 Adding new cooling channels (fixed mould plate) [6]

Fig. 14 shows that four new tempering channels were added at distance of 95 mm and 150 mm, and at a height of 28 mm from the mould parting plane. During the first iteration of optimising the tempering system, the initial channel diameter of 6 mm was maintained. Fig. 15 represents the efficiency of the cooling channel after the first phase of optimisation the tempering system.

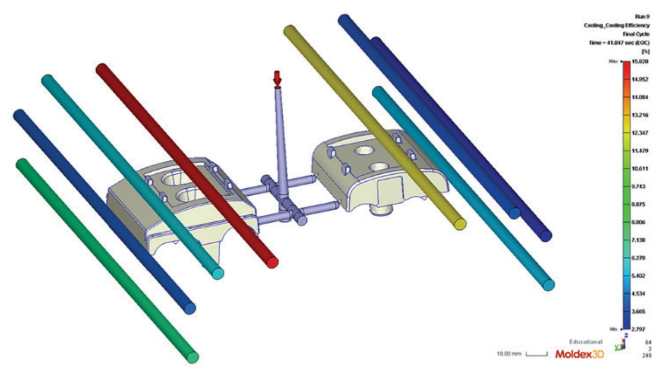

Figure 15 Cooling efficiency optimisation - first iteration [6]

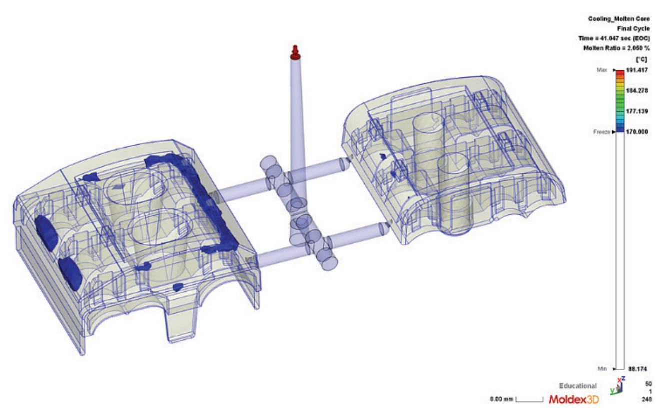

Figure 16 Percentage of unsolidified melt – first iteration [6]

According to the simulation results, it can be concluded that the efficiency of the subsequently added channels is not significantly higher compared to the existing ones (max.

15,8 %), it is about 3 % difference. In this case, remaining percentage of the melt at the end of the cooling phase is shown in Fig. 16.

Based on the previous figure, it can be concluded that the percentage of melt has decreased to 2,06 %, which is less than the current percentage of 3,54 %. From Fig. 16, the largest decrease in the percentage of melt occurred in the mould cavity that forms the upper part of the clamp housing, in the area below the subsequently added cooling channel. As for the mould cavity of the lower part there is a small percentage of the remaining melt that can be ignored.

The second optimisation iteration of the tempering system includes adding new cooling channels as well as an increase their diameter from 6 mm to 8 mm. In that case the efficiency of the channels remained the same as in the first optimisation iteration. Fig. 17 shows the results of the analysis of the unsolidified melt at the end of the cooling phase in the second optimisation iteration for the cooling system. The results show again that there are no significant improvements with the increase cooling channels diameter. The percentage of the melt after the second optimisation iteration is 1,99 %, which is only 0,07 % less compared to the first optimisation iteration.

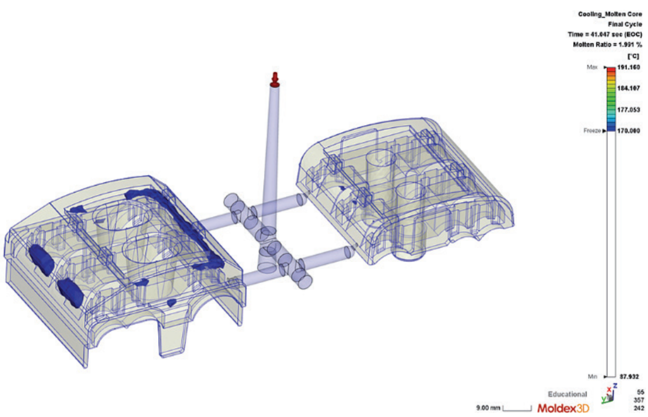

Figure 17 Percentage of unsolidified melt – second iteration [6]

Through the iteration phases of optimising the tempering system, it was concluded that it would be preferably to add additional cooling channels, and that it is enough to remain with the existing diameter of 6 mm. The ideal case would be to add more cooling channels in movable mould side, but this is not feasible due to the mould configuration. On the movable mould plate, the space is limited with the positions of the ejectors, while on the fixed mould plate care must be taken regarding the subsequent placement of the inserts for better venting of the mould cavity.

After optimising the mould runner system and cooling channels, the warpage of the part remains almost the same as in case of the initial mould. Maximal warpage is even 0,01 mm larger (compared to Fig. 11), but the warpage distribution is much more suitable because it is now accumulated in the corners of the upper part of the terminal block housing, which does not affect the assembly with lower part (Fig. 18).

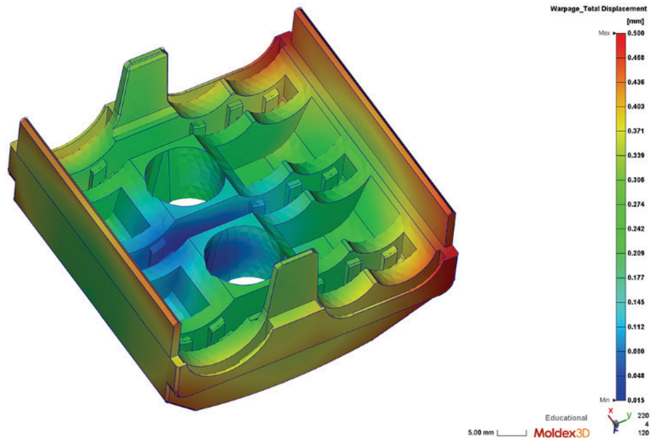

Figure 18 Optimised warpage distribution – upper part [6]

3.3 Optimisation of Mould Cavity Venting System [6]

Based on the results shown in Fig. 8, the following solutions can be suggested. As for venting in the fixed mould plate, it is possible to make inserts for cavity venting. Fig. 19 shows a CAD model of the venting insert, and the locations of these inserts in the fixed moulding plate (view from the parting plane).

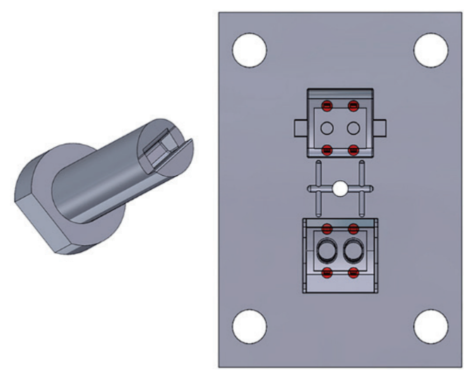
Figure 19 Air venting insert CAD model and locations at mould parting plane [6]

The arrangement of the venting mould inserts in relation to the cooling channels (avoiding collisions) is shown in Fig. 20.

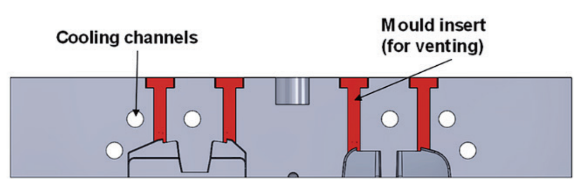

Figure 20 Arrangement of venting inserts in fixed mould plate [6]

Venting in the assembly of the movable mould plate can be performed using the ejectors. In this case, the ejectors need to be shaped as shown in Fig. 21 – grinded tangentially from 0,01 to 0,05 mm to allow the air but prevent the melt to escape from cavity. Shaping the ejectors in this way does not represent a major change in the mould, but it can improve the venting of the mould cavities.

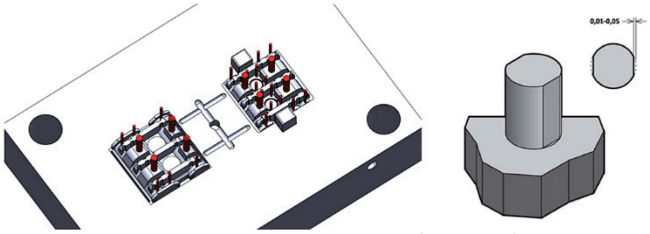

Figure 21 Tangential ejector shaping for venting [6]

4 CONCLUSIONS

The aim of this paper was to present the application of computer simulation of the injection moulding process in order to optimise the existing process and mould. Based on the obtained simulation results, several problematic phenomena were observed during the process, i.e. non-uniform filling of mould cavities, a large number of potential places of formation of air pockets and inefficient configuration of the cooling channels.

In the first step, the runner system was optimised to achieve a uniform filling of both mould cavities. After the optimisation of the runner system, the optimisation of the tempering system continued with the aim of finding a more efficient configuration of the cooling channels. When defining the additional cooling channels, it was necessary to pay attention to the possible subsequent installation of inserts for venting the mould cavity, and accordingly leave enough free space. The obtained results showed that the idea of introducing additional channels was justified, but without the need to increase the channel diameter. By introducing additional channels, the percentage of melt within the moulded part at the end of the cooling process was reduced by 3,54 %, which improvement compared to the initial injection moulding process.

Finally, within the optimisation of the venting system based on the obtained simulation results, two modifications of the existing mould were suggested: production of mould inserts in a fixed mould plate and tangential grinding the ejectors in movable mould plate.

Optimisations of the mould runner and cooling system have the positive impact also on the warpage of the moulded part in form of more suitable distribution over the upper housing part geometry.

As part of this paper, computer simulation was used to detect existing problems on the manufactured mould, and in addition, it was used to find solutions so that the previously described problems could be eliminated as effectively as possible. Within the virtual environment, it is very easy to change the dimensions of the runner system and/or processing parameters and try different combinations. In this specific case, as the simulation was performed for already made mould, its design limitations were considered. Therefore, the injection moulding simulation results are only sub-optimal.

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6 REFERENCES

[1] Jen, T.-C., Mharakurwa, E. T., Otieno, S. O., Mwema, F. M., & Wambua, J. M. (2024). *Injection Molding Process Modelling: Statistics, CAE, and AI Applications* (1st ed.). CRC Press. https://doi.org/10.1201/9781003492498

[2] Knoll, J., & Heim, H.-P. (2024). Analysis of the Similarity between Injection Molding Simulation and Experiment. *Polymers, 16*(9), 1265. https://doi.org/10.3390/polym16091265

[3] Ramesh, S., Nirmala, P., Ramkumar, G., Sahoo, Satyajeet, Anitha, G., Gnanasekar, A. K., & Isaac Joshua Ramesh Lalvani, J. (2021). Simulation Process of Injection Molding and Optimization for Automobile Instrument Parameter in Embedded System. *Advances in Materials Science and Engineering*, 10 pages. https://doi.org/10.1155/2021/9720297

[4] Li, J., Zhao, C., Jia, F. et al. (2023). Optimization of injection molding process parameters for the lining of IV hydrogen storage cylinder. *Sci Rep, 13*, 665. https://doi.org/10.1038/s41598-023-27848-1

[5] Pyata, A., Nikzad, M., Vishnubhotla, S. S., Stehle, J., & Gad, E. (2020). A simulation-based approach for assessment of injection moulded part quality made of recycled olefins. *Materials Today: Proceedings, 46*, 311-319. https://doi.org/10.1016/j.matpr.2020.08.169

[6] Sever, M. (2024). Injection moulding process optimisation with computer simulation. *M.Sc. Thesis*, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb

[7] Godec, D., Brnadić, V. & Breški, T. (2021). Optimisation of Mould Design for Injection Moulding – Numerical Approach. *Tehnički glasnik, 15*(2), 258-266. https://doi.org/10.31803/tg-20210531204548

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A Machine Vision Approach to Assessing Steel Properties through Spark Imaging

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Abstract: Accurate and efficient evaluation of steel properties is crucial for modern manufacturing. This study presents a novel approach that combines spark imaging and deep learning to predict carbon content in steel. By capturing and analyzing sparks generated during grinding, the method offers a fast and cost-effective alternative to conventional testing. Using convolutional neural networks (CNNs), the proposed models demonstrate high reliability and adaptability across different steel types. Among the tested architectures, MobileNet-v2 achieved the best performance, balancing accuracy and computational efficiency. The findings highlight the potential of machine vision and artificial intelligence in non-destructive steel analysis, providing rapid and precise insights for industrial applications.

Keywords: Carbon Content Prediction; Convolutional Neural Networks; Deep Learning; Machine Vision; Spark Imaging; Steel Analysis

1 INTRODUCTION

Rapid and reliable determination of carbon content in steel is crucial for quality control in industrial manufacturing, as carbon significantly influences steel properties such as strength, hardness, and durability. Conventional techniques for assessing carbon content, including chemical analysis methods like optical emission spectroscopy and combustion analysis, are accurate but often require extensive sample preparation, specialized laboratories, and substantial time, making them less suitable for rapid, in-line inspection in manufacturing environments [1, 2].

An alternative, traditional method known as the spark test involves observing the characteristics of sparks generated when steel is ground against an abrasive wheel. Spark patterns, such as brightness, shape and stream length, vary according to carbon content, allowing experienced technicians to make qualitative assessments quickly. However, this manual method is highly subjective and lacks quantitative precision [2].

To overcome these limitations, researchers have explored the potential of spark imaging coupled with automated image analysis techniques. Prior studies demonstrated promising results in classifying steels into broad carbon categories using automated image processing methods. Nakata et al. [1] automated spark testing to measure carbon content through controlled imaging and machine-learning analysis. Similarly, Benjawilaikul and Kaewwichit (2022) [3] reported high accuracy in categorizing carbon steels by extracting visual features from spark images using traditional machine learning approaches. These initial efforts highlighted the potential for automating spark analysis but were often limited by the reliance on manually selected image features.

Recent advancements in deep learning, particularly convolutional neural networks (CNNs), offer a powerful solution to automatically capture complex visual features directly from raw image data, eliminating subjective human interpretation and manual feature engineering. CNNs have been successfully applied in various material science tasks, including identifying microstructural features and classifying alloys and metals [4-6]. Specifically, deep learning has been shown to enhance accuracy and robustness significantly over traditional machine-learning methods in image-based material characterization [7].

In line with these advancements, our study proposes a machine vision approach that leverages spark imaging and CNNs to predict steel carbon content rapidly and non-destructively. We employ three CNN architectures: ResNet, MobileNet, and VGG. We evaluated their performance in predicting precise carbon content from spark images. Each CNN architecture provides distinct advantages:

- ResNet (Residual Network) includes skip connections that facilitate training deeper models, significantly improving accuracy [8].
- MobileNet is designed for computational efficiency, using depth wise separable convolutions, making it suitable for real-time industrial applications [9].
- VGG, known for its straightforward deep convolutional layer structure, offers robust image recognition performance, albeit at increased computational cost [10].

By integrating these CNN models into a spark imaging workflow, our approach provides an efficient, accurate, and reproducible method for assessing steel carbon content.

2 METHODOLOGIES

2.1 Experimental Setup

The experiment was performed using 75 different steel samples provided by Štore Steel d.o.o. Fig. 1 illustrates all the steel samples utilized during the experimental procedure. Each sample underwent grinding tests to generate sparks, which were captured using a customized CNC grinding setup. A ceramic grinding pin (40 mm diameter, 10 mm height, grain size K30) suitable for grinding steel and cast iron was used for grinding. To ensure consistent grinding force, a pneumatic cylinder with a proportional electro-pneumatic pressure regulator (Enfield TR-010-g10-s) was utilized. A constant pressure of 0.6 bar was applied, producing a steady grinding force of approximately 75.4 N.

Figure 1 Steel samples used in experiment

The experimental setup during grinding of steel samples is shown on Fig. 2. This figure also clearly indicates the positions of the grinding tool, steel sample, camera, and pneumatic cylinder within the setup.

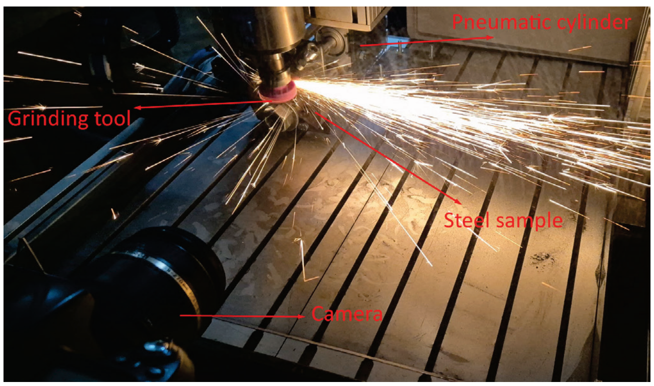

Figure 2 Experimental setup and grinding process

Spark images were captured using a Nikon D90 camera equipped with a 23 mm focal length lens, positioned strategically behind the grinding wheel. The camera was set to capture images at a resolution of 3216 × 2136 pixels.

Figure 3 Example of captured spark image

Camera parameters were carefully selected (shutter speed of 1/160 s, aperture f/8, ISO 200, and white balance set at 2500 K) to ensure optimal image quality. These settings effectively eliminated the influence of external lighting and environmental conditions, as sparks emitted during grinding were the brightest elements captured by the camera. Consequently, the background, tools, and other surroundings remained invisible, ensuring consistent image capture conditions and reliable spark feature extraction.

For each steel sample, sparks were recorded across four separate grinding cycles, resulting in approximately 60 spark images per sample. An example of a captured spark image is presented in Fig. 3.

2.2 Image Preprocessing

Captured spark images required preprocessing before use in CNN model training. Initial images (3216 × 2136 pixels) contained substantial irrelevant black background information. Consequently, images were cropped to dimensions of 1400 × 900 pixels, capturing only the relevant spark regions. Further, images were resized to 350 × 225 pixels to enhance computational efficiency. MATLAB R2023b software was employed for these preprocessing steps, enabling accurate isolation of spark characteristics relevant for carbon content prediction. Fig. 4 presents the preprocessing steps applied to spark images, including cropping to remove irrelevant background and resizing for efficient CNN model training.

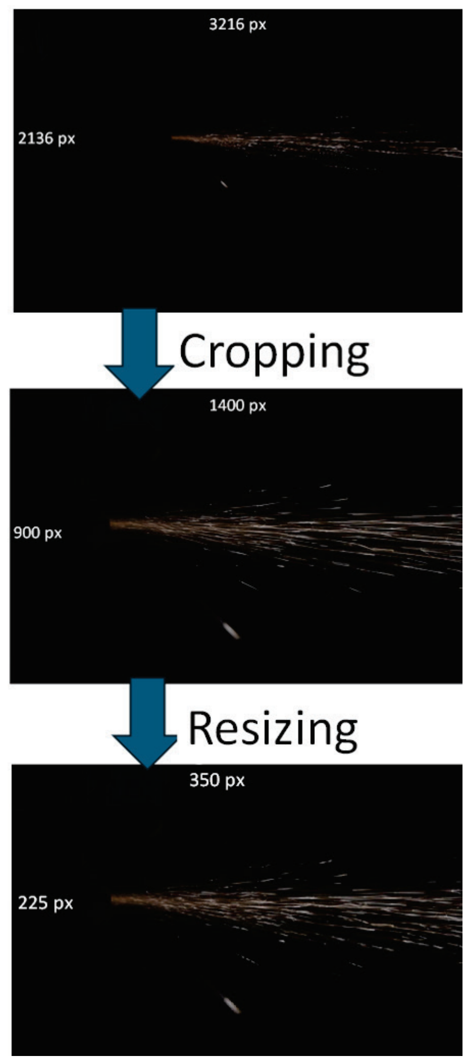

Figure 4 Steps of image preprocessing – cropping and resizing of spark images

2.3 CNN Model Development and Training

To predict steel carbon content based on spark image characteristics, three convolutional neural network (CNN) architectures were specifically chosen: ResNet-50, MobileNet-v2, and VGG-16. These architectures were selected primarily due to their immediate availability within MATLAB's Deep Learning Toolbox [11], facilitating efficient model implementation and ensuring robust support for training and validation procedures.

Moreover, these architectures were strategically chosen to represent diverse computational complexities, network depths, and parameter counts, providing a comprehensive assessment of the trade-offs between accuracy and computational resources:

- ResNet-50: With 50 layers and approximately 25.6 million learnable parameters, ResNet-50 includes residual (skip) connections that effectively alleviate issues related to training deeper networks. This architecture is particularly known for its high accuracy and robustness in complex visual tasks.
- MobileNet-v2: With 53 layers but only around 3.5 million learnable parameters, MobileNet-v2 emphasizes computational efficiency through depthwise separable convolutions. Its lightweight design makes it highly suitable for real-time industrial applications where computational resources may be constrained.
- VGG-16: Featuring 16 layers and about 138 million learnable parameters, VGG-16 is characterized by its straightforward yet deep convolutional structure, providing robust image recognition performance. However, its higher parameter count entails greater computational costs and resource requirements compared to the other two models.

These selections enabled a thorough comparative analysis across architectures of significantly different depths and computational footprints, ultimately guiding the identification of a balanced and practical solution for industrial deployment.

CNN models were adapted through transfer learning from pre-trained models, modifying both the input and output layers to transform the architectures from classification into regression models suitable for predicting carbon content. Specifically, the image input layer was modified to accept images with dimensions of 225 × 350 pixels. Additionally, the final three layers of each CNN model—fc1000, fc1000_softmax and the classification layer were removed. In their place, six new layers were added: three fully connected layers with 256, 128, and 1 neuron, respectively, interleaved with three ReLU activation layers. These modifications enabled the CNNs to output a continuous value corresponding to carbon content. The structural changes are illustrated in Fig. 5.

The training utilized MATLAB R2023b with the Deep Learning Toolbox [11]. Training parameters were standardized across all architectures:

- Epochs: 50
- Mini-batch size: 64
- Learning rate: 0.001
- Optimizer: Adam.

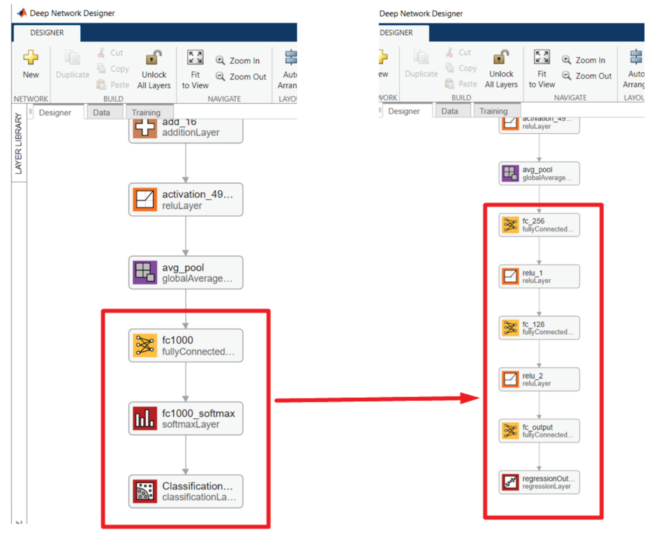

Figure 5 Modification of CNN architectures from classification to regression models

Models were validated using five-fold cross-validation [12] to ensure robustness and reduce bias. Tab. 1 shows the distribution of 75 steel samples used in five-fold cross-validation, listed by their batch (sarge) values. Each fold contained 15 unique samples, ensuring representative coverage of various carbon contents across the training and testing datasets. This division enabled robust evaluation and minimized bias in assessing the performance of the CNN models.

Table 1 Distribution of steel samples in five-fold cross-validation

Fold1	Fold2	Fold3	Fold4	Fold5
91563	93677	93646	93322	93668
92456	91461	92213	93647	92326
91457	92415	93541	92250	92713
91959	93746	92252	93797	93802
92423	92412	92147	92065	93644
92369	91802	92781	91942	91677
91724	93139	92331	93137	91721
92062	93645	92329	91943	93696
93278	92715	93511	92613	92251
91688	92718	92624	92710	93516
91958	93648	92047	92716	92623
93545	92253	91678	93544	93518
93706	91792	92943	92249	93873
92424	92622	93642	92145	92796
93675	92330	92328	92471	92215

2.4 Evaluation Metrics

The performance of each CNN model was evaluated using Mean Absolute Percentage Error (*MAPE*), Root Mean Squared Error (*RMSE*) and the coefficient of determination (R^2). These metrics provided comprehensive quantitative measures of prediction accuracy and model explanatory power. Lower *MAPE* and *RMSE* values indicate higher prediction accuracy, whereas R^2 values closer to 1 indicate a better fit of the regression model to the actual data. Training times were also recorded to assess computational efficiency, crucial for practical applicability in industrial scenarios. Detailed comparisons of these metrics are presented in Chapter 3.

3 RESULTS

The predictive performance of each CNN model was evaluated based on *MAPE*, *RMSE*, and R^2 metrics, summarized across five-fold cross-validation.

MAPE results are presented in Tab. 2 and Fig. 6. This metric represents the relative error percentage between the predicted and actual carbon content values. MobileNet-v2 achieved the lowest average *MAPE* (14.52%), making it the most accurate model. ResNet-50 followed with an average *MAPE* of 17.01%, while VGG-16 exhibited the highest error at 21.09%, indicating weaker predictive performance.

Table 2 Mean Absolute Percentage Error (MAPE) for each model across five folds

MAPE (%)	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5	Average
ResNet50	14.85	11.55	18.82	19.38	20.43	17.01
MobileNet-v2	15.39	12.10	13.13	19.37	12.62	14.52
VGG-16	24.52	19.11	17.10	25.74	18.99	21.09

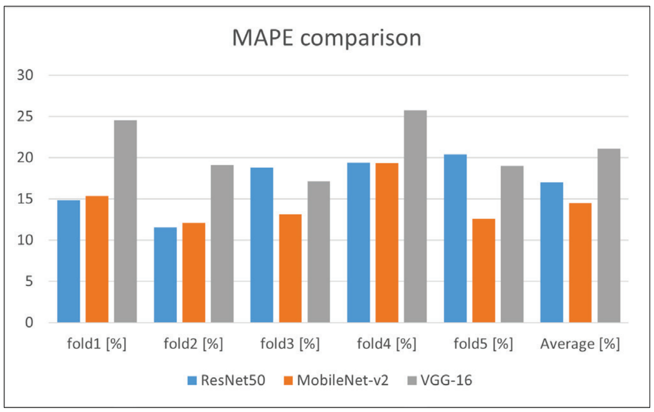

Figure 6 Comparison of Mean Absolute Percentage Error (*MAPE*) across different CNN models

RMSE values are summarized in Tab. 3 and Fig. 7, providing an absolute measure of prediction error. Once again, MobileNet-v2 showed the lowest RMSE (0.0623), followed by ResNet-50 (0.0665) and VGG-16 (0.0705). These results align with the *MAPE* findings, further confirming that MobileNet-v2 was the most effective model in reducing absolute prediction errors for carbon content.

Table 3 Root Mean Squared Error (*RMSE*) for each model across five folds

RMSE	Fold 1	Fold 2	Fold 3	Fold 4	Fold 5	Average
ResNet50	0.0887	0.0631	0.0650	0.0616	0.0543	0.0665
MobileNet-v2	0.089	0.0659	0.0480	0.0595	0.0492	0.0623
VGG-16	0.0983	0.07	0.0588	0.0685	0.0568	0.0705

R^2 metric, shown in Fig. 8, clearly demonstrated that MobileNet-v2 provided the highest average explanatory power (R^2 = 0.786), signifying strong model performance. ResNet-50 demonstrated a moderate average R^2 of 0.683, whereas VGG-16 had the lowest explanatory power with an average R^2 of 0.495.

The computational efficiency of each model was assessed based on training time, as shown in Fig. 9.

MobileNet-v2 had the shortest training time at 5.13 minutes, making it not only the most accurate but also the fastest to train. VGG-16 was the slowest, taking 9.18 minutes, due to its deeper architecture and higher parameter count.

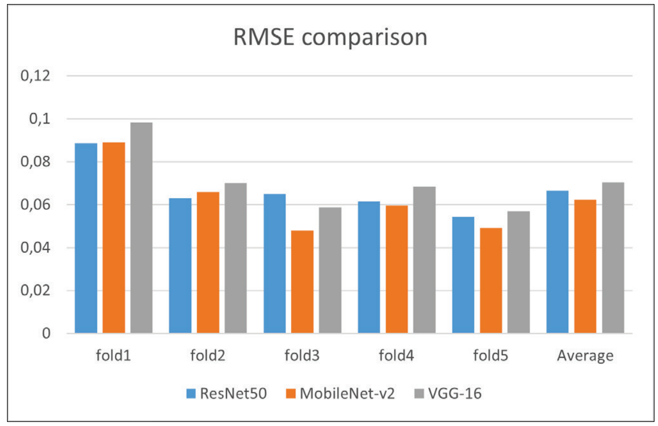

Figure 7 Comparison of Root Mean Squared Error (*RMSE*) across different CNN models

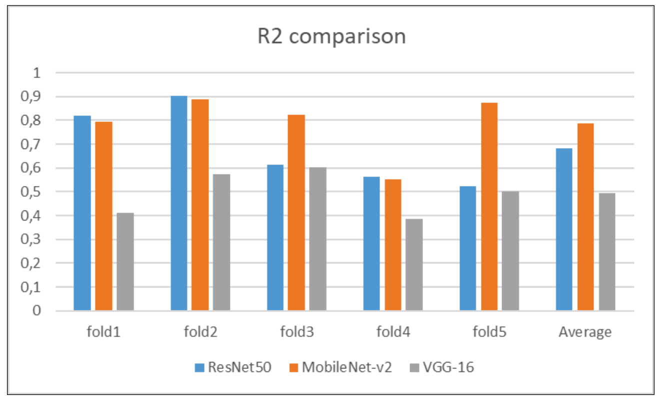

Figure 8 Comparison of Coefficient of determination (R^2) across different CNN models

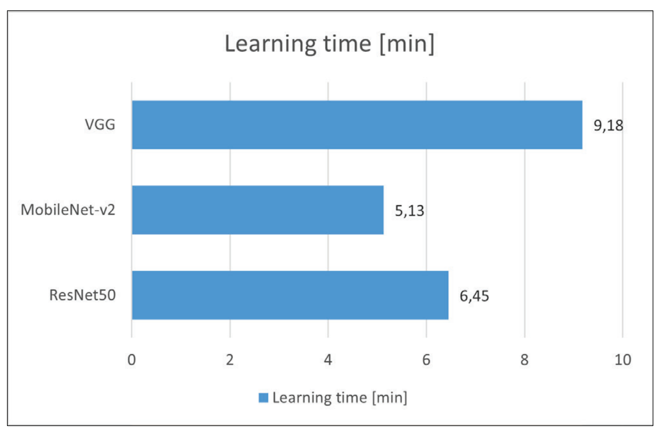

Figure 9 Training time comparison for different CNN models

4 CONCLUSIONS

This study explored the application of CNNs for predicting carbon content in steel based on spark images. Three different architectures (ResNet-50, MobileNet-v2, and VGG-16) were evaluated using a five-fold cross-validation approach, assessing their prediction accuracy and computational efficiency.

The results demonstrated that MobileNet-v2 outperformed both ResNet-50 and VGG-16, achieving the lowest *MAPE* of 14.52%, lowest *RMSE* of 0.0623 and highest coefficient of determination (R^2) of 0.7861. Additionally, MobileNet-v2 required the shortest training time of 5.13 min, making it the most efficient model. While ResNet-50 provided competitive accuracy (*MAPE*: 17.01%, *RMSE*: 0.0665, R^2: 0.68372), it was slightly slower (6.45 min). In contrast, VGG-16 showed the highest errors (*MAPE*: 21.09%, *RMSE*: 0.0705, R^2: 0.49508) and the longest training time (9.18 min), indicating that it may not be the most suitable model for this task. MobileNet-v2 is the most suitable model for industrial applications, offering efficiency and accuracy for real-time steel classification.

The current dataset of 75 steel samples yielded promising predictive accuracy. However, to enhance model robustness and generalization for broader industrial application, future work will involve expanding our database by including more steel samples and a wider variety of steel materials. Additionally, incorporating advanced CNN architectures, hybrid machine-learning methods, and attention visualization techniques, such as attention maps or saliency analyses, will be considered. These visualization methods would enhance the decision-making process of CNN models by identifying critical spark image regions influencing predictions. This study primarily aimed to demonstrate the feasibility of predicting steel carbon content using CNNs and spark imaging; further refinements will provide more detailed insights into model interpretability and practical implementation.

Overall, this research highlights the significant potential of machine vision combined with deep learning for rapid, accurate, and non-destructive steel property analysis in industrial settings.

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5 REFERENCES

[1] Nakata, T. (2012). Development of automated spark testing technique by image processing to measure carbon content in steel materials. *IFAC Proceedings Volumes*, *45*(23), 118-119. https://doi.org/10.3182/20120910-3-JP-4023.00029
[2] See https://www.ispatguru.com/spark-testing-of-steels/.
[3] Benjawilaikul, T., & Kaewwichit, T. (2022). Classification of Carbon Steels by Automated Spark Test Technique Using Feature Extraction Based on Machine Learning Image Processing: DOI: 10.14416/j.ind.tech.2022.08.005. *The Journal of Industrial Technology*, *18*(2), Article 2.
[4] Azimi, S. M., Britz, D., Engstler, M., Fritz, M., & Mücklich, F. (2018). Advanced steel microstructural classification by deep learning methods. *Scientific reports*, *8*(1), 2128. https://doi.org/10.1038/s41598-018-20037-5
[5] DeCost, B. L., Francis, T., & Holm, E. A. (2017). Exploring the microstructure manifold: image texture representations applied to ultrahigh carbon steel microstructures. *Acta Materialia*, *133*, 30-40. https://doi.org/10.1016/j.actamat.2017.05.014
[6] Zhang, Z., Mativenga, P., Zhang, W., & Huang, S. Q. (2024). Deep Learning-Driven Prediction of Mechanical Properties of 316L Stainless Steel Metallographic by Laser Powder Bed Fusion. *Micromachines*, *15*(9), 1167. https://doi.org/10.3390/mi15091167
[7] Xu, H., Xu, Z., & Zhang, K. (2019, November). Mechanical properties prediction for hot roll steel using convolutional neural network. In *International Conference on Bio-Inspired Computing: Theories and Applications* (pp. 565-575). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-15-3415-7_47
[8] He, K., Zhang, X., Ren, S., & Sun, J. (2016). Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 770-778). https://doi.org/10.4128/9781606492147
[9] Howard, A. G., Zhu, M., Chen, B., Kalenichenko, D., Wang, W., Weyand, T., ... & Adam, H. (2017). Mobilenets: Efficient convolutional neural networks for mobile vision applications. *arXiv preprint arXiv:1704.04861*.
[10] Simonyan, K., & Zisserman, A. (2014). Very deep convolutional networks for large-scale image recognition. *arXiv preprint arXiv:1409.1556*.
[11] MathWorks (2023). MATLAB Deep Learning Toolbox, R2023b. The MathWorks Inc., Natick, Massachusetts, USA. Available: https://www.mathworks.com/products/deep-learning.html
[12] Fushiki, T. (2011). Estimation of prediction error by using K-fold cross-validation. *Statistics and Computing*, *21*, 137-146. https://doi.org/10.1007/s11222-009-9153-8

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Integration Possibilities of Logistics Process Simulation and VR Technology

Péter Tamás

Abstract: Due to the rapidly changing market environment and the increasing complexity of processes, the simulation-based analysis of logistics processes is gaining growing significance. Simulation provides an opportunity to analyse and optimize logistics systems, as well as to conduct preliminary testing before implementation. Virtual reality (VR) can complement this by supporting design, decision-making, and training processes. The primary aim of this publication is not to present simulation modelling or VR technology in general, but rather to examine their potential applications and integration in logistics, with particular attention to synergistic benefits. The most important development directions related to these technologies have been identified. The study focuses on the integration potential of the two fields, which offers new opportunities to enhance efficiency in logistics. The research methodology is inductive, meaning the study was carried out using knowledge gained from practical experience and literature analysis. In addition to exploring and summarizing integration opportunities, the paper also presents the anticipated benefits, providing motivation for applying the solution and for further research in the field.

Keywords: Logistics; Process Development; Simulation; Virtual Reality

1 INTRODUCTION

The dynamic technological advancements of today are introducing new opportunities in the field of logistics process development. Numerous Industry 4.0 solutions have been increasingly adopted in logistics (e.g., VR, AR, Digital Twin, etc.); however, exploring the integration possibilities of these solutions and their application in logistics presents a significant challenge for logistics professionals [1-2]. The high-level visualization and interactive analysis of current and future processes are playing an increasingly important role in logistics process development, where the application of simulation modeling and VR technologies is a key factor [3-4].

It is essential to clarify the meaning of these concepts. Logistics simulation is a method capable of realistically modeling processes and systems, allowing for the evaluation of their state changes [5]. Virtual reality (VR) technology, on the other hand, is a computer-generated interactive environment that provides users with an immersive experience, enabling them to learn, work, or engage in entertainment within realistic simulated scenarios [6]. These technologies can contribute to improving the efficiency of a logistics system in various ways [7], such as through more effective employee training, faster identification of emerging issues, and providing an objective evaluation of different system variations. In this study, I applied the systematic literature review method to explore the relevant types of logistics simulation and VR technologies, as well as their development directions. One of these directions is the integration of the two fields, whose possibilities and the benefits achievable through integration are analyzed in this paper.

2 SYSTEMATIC LITERATURE REVIEW TO IDENTIFY THE RESEARCH GAP

To explore the development of the examined field, as well as to identify current research gaps and development opportunities, I applied the systematic literature review method [8]. The steps of the method are shown in Fig. 1.

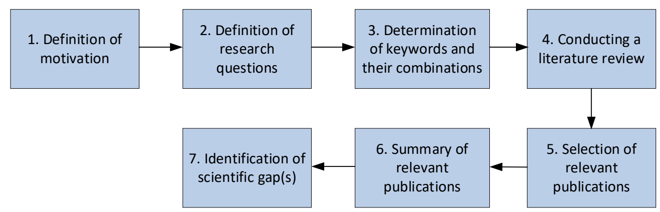

Figure 1 Steps of the Systematic Literature Review

Steps of the Systematic Literature Review:

1. ***Defining Motivation:*** Simulation modeling and VR technologies are undergoing significant transformations, and exploring their current types and integration possibilities may lead to new, previously unknown benefits.
2. ***Defining Research Questions:*** During the literature analysis of the research topic, I seek answers to the following questions:

- What are the main types and application areas of simulation modeling and VR technologies?
- What are the objectives of applying these technologies?
- What research directions can be identified?

3. ***Defining Keywords and Their Combinations:*** To answer the research questions, the focus during the definition of keywords was limited solely to the topics of logistics simulation and VR technologies; therefore, similar technologies such as augmented reality and mixed reality were not included in the scope of the search. The search keywords were as follows::

- "logistics" OR "supply chain"
- "process simulation" OR "simulation technologies"
- "VR" OR "Virtual Reality"

Keyword Search Combinations:

- ("logistics" OR "supply chain")
- ("logistics" OR "supply chain") AND ("process simulation" OR "simulation technologies")
- ("logistics" OR "supply chain") AND ("process simulation" OR "simulation technologies") AND ("VR" OR "Virtual Reality").

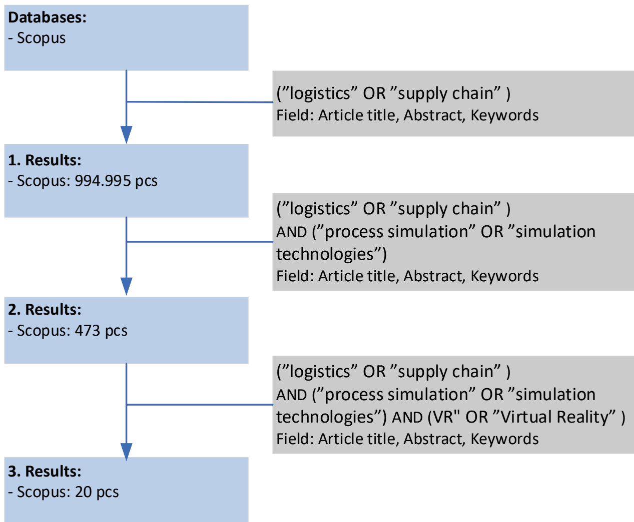

Figure 2 Process of Literature Analysis

4. ***Conducting the Literature Analysis:*** For the literature review, the Scopus database was used without any time restrictions. The main reasons for choosing this database were its recognition within the international scientific community and the fact that nearly all high-quality scientific journals are indexed by Scopus, enabling a comprehensive analysis. Using the search functions provided by the database, filters were applied simultaneously to article titles, abstracts, and keywords, as illustrated in Fig. 2. As a result of the filtering process, 473 journal articles were selected.
5. ***Selection of Relevant Publications:*** Based on the review of the abstracts of the publications resulting from the filtering process, as well as additional searches conducted on scholar.google.com, a total of 40 publications were selected for detailed analysis.
6. ***Summary of Examined Publications:*** Based on the content review of the selected publications, three key areas were summarized:

- Simulation modeling in logistics
- Application of VR technology in logistics
- Development directions of these technologies.

Simulation Modeling in Logistics:

The application possibilities of simulation modeling in logistics are clearly described by the Digital Twin concept, which can be classified into different levels of maturity. These include the Digital Model, Digital Shadow, and Digital Twin concepts [9-10]. The level of advancement depends on the way in which a bidirectional connection is established between the physical entity and the digital model (Figure 3). Additionally, it is important to note that in the case of a Digital Model, not only physical entities but also the concepts aimed at their creation can be analysed.

Digital Twin Maturity Levels:

- In the Digital Model approach, a simulation model is created based on a physical entity or a developed future concept. After analyzing the simulation, the physical entity or conceptual design is further optimized. As an example, the authors of [11] developed digital models for baggage handling systems to support the selection of optimal development alternatives.

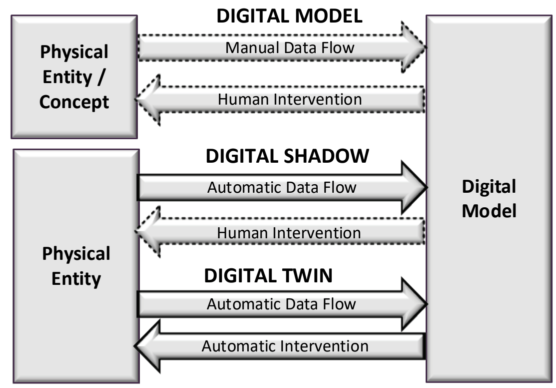

Figure 3 Digital Twin Concept

- In the case of a Digital Shadow, the simulation model automatically receives data from the physical object. After processing this data, it provides recommendations to improve the operation of the examined physical entity. The authors of [12] implemented a Digital Shadow model to enhance the efficiency of the floorball manufacturing process. The model enabled real-time monitoring of the production environment, where energy consumption and production data were collected to identify the most energy-intensive processes. Based on these insights, production plans were developed to minimize energy consumption and optimize production efficiency.
- In the case of a Digital Twin, bidirectional and automatic communication exists between the physical object and the simulation model. The authors of [13] applied the Digital Twin concept in glass lens manufacturing, where real-time data from the physical environment was processed with the support of artificial intelligence. This integration enhanced manufacturing efficiency, improved production accuracy, and reduced resource consumption.

The following key objectives of logistics simulation implementation can be distinguished [5]:

- Avoiding Design Errors: Simulation analysis conducted before the implementation of future developments helps prevent design errors. This includes avoiding inappropriate facility layouts and suboptimal selection of material handling and technological equipment.
- Comparing Design Alternatives: Simulation is applied when multiple alternatives (e.g., different layouts, processes, or types of technological equipment) exist for a development. In such cases, simulation is used to define KPI indicators that require modeling to support decision-making in alignment with the company's criteria.
- Determining Performance Limits and Capacity Requirements: Simulation modeling techniques can be used to assess the capacity needs and performance thresholds of existing systems or planned investments. This includes evaluating intermediate storage and warehouse capacities, as well as maximum production

capacity, allowing for accurate and timely definition of development phases.
- Comparing Control Strategy Variants: To achieve the optimal operation of a logistics system, different control strategies (e.g., warehouse material handling strategies, production line service strategies) can be defined. After conducting a simulation analysis, decision-making methods can be applied to select the most suitable alternative.
- Modeling Operational Disruptions and Their Mitigation: Logistics systems may encounter operational disruptions, breakdowns, and accidents. The development of scenarios for effectively managing such issues can be significantly supported by the capabilities of simulation modeling.
- Optimizing Logistics Processes: The operation of current or future logistics systems can be optimized using simulation models. For example, synthetic data generated by simulation models can be used to determine optimal production schedules, transportation routes, and layout plans.

Overall, it can be stated that these objectives can be achieved for all logistics processes through the application of customized Digital Model, Digital Shadow, or Digital Twin concepts. The implementation of a simulation model can be carried out either by developing custom software or by using frameworks (e.g., Plant Simulation, Simul8). Based on experience, the use of frameworks is prioritized due to their shorter development time requirements.

Application of VR Technology in Logistics:

Virtual reality (VR) can be classified based on different criteria, including the level of immersion and interactivity. According to the level of immersion, VR can be categorized into non-immersive, semi-immersive, and fully immersive types [14]. The fundamental difference lies in how much the user feels physically present in the virtual space [14].

Types of Virtual Reality Based on the Level of Immersion [14]:
- Non-Immersive VR: In this case, the user interacts with and controls the virtual environment through a screen, such as in the simulation model of a planned flexible manufacturing system [15].
- Semi-Immersive VR: This category includes systems that partially surround the user with a virtual environment. Examples include CAVE systems (Cave Automatic Virtual Environment), where walls, floors, and ceilings function as projection screens, as well as curved screens and projector-based systems [14].
- Fully Immersive VR: Fully immersive VR is represented by head-mounted displays (HMDs) such as Oculus Rift and HTC Vive, which provide real-time motion tracking and interactive capabilities for a fully immersive experience [16].

Based on the literature [17-19], the following levels of interactivity can be distinguished:
- Passive: The user is merely an observer of events (e.g., watching a VR movie or a simulation).
- Limited: The user can interact with the environment only by selecting predefined functions (e.g., interactive walkthrough, menu selection).
- Active: The user can freely manipulate objects in the virtual environment, which influences the outcome of the simulation (e.g., VR object manipulation, interactive simulation).
- Immersive Interactivity: Active interaction is complemented by physical sensations, including weight, texture, and force feedback, allowing the user to not only see and move objects but also feel them (e.g., haptic gloves, full-body tracking).

VR solutions can also be combined with various other technologies. The most commonly applied solutions include:
- Mixed Reality (MR) [20]: In this case, the real world and digital elements interact. MR is a combination of Augmented Reality (AR) and Virtual Reality (VR), where the user can not only see digital elements integrated into the real world but also manipulate them. In MR, digital elements appear as part of the real world, and the user can interact with them actively. Example: Using Microsoft HoloLens, the user can place virtual objects in real spaces (e.g., a virtual 3D model on a table), and these objects interact with the real environment. For instance, virtual objects do not fall off the table if a real physical object is present.
- The Metaverse [6]: The Metaverse is a shared virtual space created by integrating Virtual Reality (VR), Augmented Reality (AR), blockchain technology, and other digital innovations [6]. Its main areas of application include: virtual campuses, economic activities, art galleries gaming platforms. Examples: Decentraland, The Sandbox, and Meta's virtual spaces, where users can interact, trade, and build within persistent virtual environments.

The presented technologies and their types are summarized in Fig. 4. Since all levels of interactivity can occur across different types, their representation is omitted.

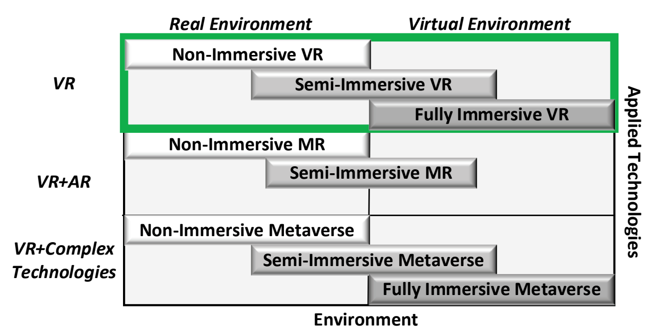

Figure 4 Types of Virtual Reality (VR)

The relevant objectives for the application of VR technology in logistics (variants marked with a green frame in Fig. 3) are as follows:
- Education and Training: Virtual reality enables the training [7, 21] and education of any logistics process. Its advantages include significantly reducing training costs and time requirements in certain cases, as well as

minimizing safety risks. Examples include training in the operation of various types of material handling equipment or the functioning of complex logistics processes. The technology can be applied in both educational institutions [22-25] and the corporate sector [26-27].

- Eliminating Design Errors: By conducting interactive examinations of designed logistics systems in a VR environment, design flaws can be identified and corrected before implementation [28]. An example would be ergonomic analysis of a specific workplace environment using VR technology.
- More Effective Handling of Operational Issues: Examining the real environment with VR technology enables rapid identification of operational issues and thus faster problem resolution [29-30]. For example, if the temperature in a warehouse exceeds the defined threshold, this can be indicated in the VR environment, allowing for a quicker response to the problem.
- Enhancing Customer Experience: VR technology allows customers to gain new experiences and additional information relevant to their processes. Examples include tracking a shipment in a VR environment or using VR in a restaurant to experience an artificial setting (e.g., a beach environment) or to access gastronomic information [31].

Overall, it can be concluded that VR technology offers numerous advantages in the field of logistics, as it enables cost-effective training, the elimination of design errors before implementation, the rapid identification of operational issues, and the enhancement of customer experience. As a result, it contributes to increased efficiency and competitiveness.

Development Directions of Simulation Modeling and VR Technologies:

Based on the literature analysis, the following development directions have been identified in the fields of simulation modeling and VR technologies:

- Technology Development: Further advancement of simulation modeling and VR technologies to create more user-friendly applications and new experience-driven functionalities. This includes real-time data integration, AI-based predictive features, and multi-user interactive capabilities.
- Expansion of Technology Applications: Research into new application areas beyond existing fields, such as education, healthcare, urban planning, and the development of logistics supply chains. This also involves conceptual planning and implementation of technologies to enhance competitive advantage, with a particular focus on sustainability and energy efficiency goals.
- Technology Integration: Exploration, conceptual planning, and implementation of integration possibilities between simulation modeling, virtual reality (VR), augmented reality (AR), and other emerging technologies such as IoT, blockchain, and artificial intelligence. This integration aims to support the more efficient modeling and management of complex and dynamic systems.
- Optimization of User Experience: Refinement of user experience and visualization capabilities in technological development, with a focus on intuitive controls, realistic graphics, and adaptive learning systems that facilitate faster adaptation and efficiency improvement.

3 INTEGRATION POSSIBILITIES OF LOGISTICS PROCESS SIMULATION AND VR

The integration possibilities of logistics process simulation and VR can be established based on the relationship between the alternatives of the four previously discussed aspects (Fig. 5). For a future logistics system concept under investigation, only the A. Digital Model and its related VR solutions can be integrated. This means that B. Digital Shadow and C. Digital Twin solutions, along with their associated VR applications, cannot be implemented. For an existing logistics system, the relationship between all Digital Twin maturity levels and VR types can be interpreted.

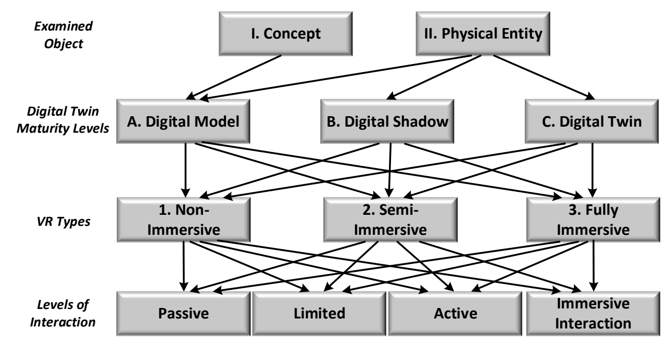

Figure 5 Integration Possibilities of Simulation Modeling and VR

Advantages Achieved Through Technology Integration:

- Improved Visualization and Intuitive Understanding: Interactive 2D/3D visualization of simulation models makes it easier to understand the examined processes.
- More Efficient Decision-Making: The ability to quickly manipulate simulated processes allows for the rapid evaluation of intervention effects, thereby reducing decision-making lead time.
- Consideration of Human Factors: In a life-size simulation model, features such as motion tracking and haptic feedback enable the assessment of worker efficiency, allowing for the optimization of working conditions before implementation.
- Faster Problem Identification and Resolution: Some design and operational issues may remain hidden in traditional simulations. However, VR applications enhance their detection (e.g., material handling obstacles, hazardous areas).
- Safer Testing Environment: Dangerous or costly processes can be examined in a safe virtual environment, reducing risks and expenses.

4 CONCLUSIONS

This paper has presented two technologies, namely simulation modeling and virtual reality (VR), along with their current types and future development directions. One of these directions is the exploration and application of integration possibilities between simulation modeling and VR technologies. Through simulation, logistics systems can be analyzed and optimized more effectively, while design errors can be identified and eliminated before implementation. By applying VR technology, visualization capabilities can be further enhanced, decision-making processes can be supported, and training processes can be made more cost-effective.

The integration of these technologies enables faster problem detection, more efficient optimization, and the creation of a safer testing environment. As a next step, concepts for implementing integration possibilities will be developed, tested, and applied in real industrial environments.

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5 REFERENCES

[1] Bányai, T., Bányainé Tóth, Á., Illés, B., & Tamás, P. (2019). *Ipar 4.0 és logisztika* (Industry 4.0 and Logistics). Miskolci Egyetem, ISBN: 978-963-358-182-7. (in Hungarian)

[2] Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine, 51*(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474

[3] Cifone, F. D., Hoberg, K., Holweg, M., & Staudacher, A. P. (2021). 'Lean 4.0': How can digital technologies support lean practices? *International Journal of Production Economics, 241*, 108258. https://doi.org/10.1016/j.ijpe.2021.108258

[4] Elafri, N., Tappert, J., Rose, B., & Yassine, M. (2022). Lean 4.0: Synergies between Lean Management tools and Industry 4.0 technologies. *IFAC-PapersOnLine, 55*(10), 2060-2066. https://doi.org/10.1016/j.ifacol.2022.10.011

[5] Tamás, P. (2021). *Innovative simulation testing methods in logistics*. Miskolc-Egyetemváros, Hungary: Miskolci Egyetem, Logisztikai Intézet., ISBN: 9789633582398.

[6] Zhang, C. (2024). The future of education: Applications of virtual reality and the metaverse. *Proceedings of the 2nd International Conference on Machine Learning and Automation*, 197-202. https://doi.org/10.54254/2755-2721/114/2024.18288

[7] Torkkel, J.-M., Lahtinen, H., Ruohomaa, H., & Salminen, V. (2024). Virtual technologies and digital twins for logistics hub development. *Human Factors, Business Management and Society, 135*, 268-275. https://doi.org/10.54941/ahfe1004953

[8] Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In Buchanan, A. D., & Bryman, A. (Eds.), *The Sage handbook of organizational research methods* (pp. 671–689). Sage Publications.

[9] Matyi, H., & Tamás, P. (2023). An innovative framework for quality assurance in logistics packaging. *Logistics, 7*(4), Article 82. https://doi.org/10.3390/logistics7040082

[10] Le, T. V., & Fan, R. (2024). Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges. *Computers and Industrial Engineering, 187*, 109768. https://doi.org/10.1016/j.cie.2023.109768

[11] Fay, B., Ramasubramanian, A. K., Murphy, R. D., Adderley, T., & Papakostas, N. (2022). Using a process simulation platform for reviewing automated airport baggage handling system configurations. *Procedia CIRP, 112*, 180-185. https://doi.org/10.1016/j.procir.2022.09.069

[12] Gutmann, T., Nyffenegger, F., Pellegrini, M., Cabrucci, A., & Guzzini, A. (2023). A digital twin-based approach for the optimization of floor-ball manufacturing. *Electronics, 12*(24), 4979. https://doi.org/10.3390/electronics12244979

[13] Shiu, S. C., Tang, K. E., & Liu, C. W. (2023). Digital twin-driven centering process optimization for high-precision glass lens. J*ournal of Manufacturing Systems, 67*, 122-131. https://doi.org/10.1016/j.jmsy.2023.01.009

[14] Ogrizović, D., Perić Hadžić, A., & Jardas, M. (2021). Fully immersive virtual reality in logistics modelling and simulation education. *Promet – Traffic & Transportation, 33*(6), 799-806. https://doi.org/10.7307/ptt.v33i6.1

[15] Molnár, Z., Tamás, P., & Illés, B. (2024). Planning of flexible manufacturing lines with AGV material handling for the entire life cycle. *Acta Logistica: International Scientific Journal about Logistics, 11*.

[16] Torkkel, J.-M., Lahtinen, H., Ruohomaa, H., & Salminen, V. (2024). Virtual technologies and digital twins for logistics hub development. *Human Factors, Business Management and Society, 135*, 268-275. AHFE Open Access. https://doi.org/10.54941/ahfe1004953

[17] Petersen, G. B., Petkakis, G., & Makransky, G. (2022). A study of how immersion and interactivity drive VR learning. *Computers & Education, 179*, 104429. https://doi.org/10.1016/j.compedu.2021.104429

[18] Ismail, A. M. A. (2024). Exploring the Levels of eLearning Interactivity: A Review of Research Literature. *Journal of Ecohumanism, 3*(7), 2997-3024. https://doi.org/10.62754/joe.v3i7.4693

[19] Fern, N., Cristea, A. I., Nolan, S., & Stewart, C. (2024). Doctoral Colloquium—How Interactivity and Presence Affect Learning in Immersive Virtual Reality: A Mixed Methods Study Design. *10th International Conference of the Immersive Learning Research Network*. https://doi.org/10.56198/U6C0WFYQB

[20] Yang, J. (2022). Visual simulation of modern supply chain based on MR virtual reality technology. *Advances in Multimedia*, Article ID 4902001, 11 pages. https://doi.org/10.1155/2022/4902001

[21] Gołda, G., Kampa, A., & Paprocka, I. (2016). The application of virtual reality systems as a support of digital manufacturing and logistics. *IOP Conference Series: Materials Science and Engineering, 145*, 042017. https://doi.org/10.1088/1757-899X/145/4/042017

[22] Wang, K. (2021). Application of virtual reality technology in higher vocational smart logistics teaching. *Journal of Physics: Conference Series, 1881*(3), 032041. https://doi.org/10.1088/1742-6596/1881/3/032041

[23] Pehlivanis, K., Papagianni, M., & Styliadis, A. (2004). Virtual reality & logistics. *Acta Universitatis Apulensis*. Retrieved from https://www.researchgate.net/publication/265405399
[24] Pletcher, T., & Medical Readiness Trainer Team. (2000). An immersive virtual reality platform for medical education: Introduction to the medical readiness trainer. *Proceedings of the 33rd Hawaii International Conference on System Sciences*. https://www.researchgate.net/publication/232632080
[25] He, D. (2022). Teaching practices of a warehousing management curriculum based on virtual reality simulation technology. *International Journal of Emerging Technologies in Learning, 17*(9), 96-103. https://doi.org/10.3991/ijet.v17i09.30939
[26] Guryeva, A. A. (2023). The use of virtual reality technology in training transport industry specialists. *SHS Web of Conferences, 164*, Article 00046. https://doi.org/10.1051/shsconf/202316400046
[27] Yang, J. (2022). Visual simulation of modern supply chain based on MR virtual reality technology. *Advances in Multimedia*, Article ID 4902001, 11 pages. https://doi.org/10.1155/2022/4902001
[28] Gabajová, G., Krajčovič, M., Rolinčinová, I., Furmannová, B., & Bučková, M. (2020). Digital design of production systems using virtual reality. *Proceedings of CBU in Economics and Business, 1*, 49-52. https://doi.org/10.12955/peb.v1.18
[29] Yao, L. J., Li, J., & Han, J. J. (2020). Application of virtual reality technology in intelligent cold chain logistics system. *Journal of Physics: Conference Series, 1651*, 012030. https://doi.org/10.1088/1742-6596/1651/1/012030
[30] Hong, S., & Mao, B. (2018). An interactive logistics centre information integration system using virtual reality. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-3, 523-529. https://doi.org/10.5194/isprs-archives-XLII-3-523-2018
[31] Mısır, S. (2024). Virtual reality and augmented reality in gastronomy businesses. In Yilmaz, O. (Ed.), *New trends and frontiers in social, human and administrative sciences* (pp. 96–107). All Sciences Academy. https://doi.org/10.5281/zenodo.14016408

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Extending a Prognostic Bearing Test Simulator with Smart Data Acquisition and Monitoring Capabilities

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Abstract: Predictive maintenance is essential for modern industrial systems, enabling early fault detection and efficient asset management. This paper presents an enhanced prognostic bearing test simulator that upgrades a laboratory platform for controlled accelerated degradation experiments. The system integrates a LabJack T7 Pro data acquisition unit with a web-based application, enabling automated data logging, structured storage, and remote visualization. These features reduce manual effort, improve data consistency, and enhance usability for real-time monitoring and experiment control. The developed platform supports diverse operating conditions and generates high-quality datasets for testing predictive maintenance strategies. The paper outlines the system architecture, data framework, and experimental validation, demonstrating its relevance for advancing diagnostics in rotating machinery.

Keywords: bearing degradation; data acquisition; predictive maintenance; smart diagnostics; web-applications

1 INTRODUCTION

Maintenance strategies have evolved from corrective and preventive approaches to advanced predictive maintenance (PdM) systems. PdM utilizes real-time monitoring, smart sensors, and AI-based analytics to detect faults and optimize intervention timing, enhancing reliability and cost efficiency.

Predictive maintenance addresses these changes by utilizing continuous monitoring and data-driven diagnostics to predict and prevent potential failures before they occur [1, 2]. It employs real-time monitoring data, advanced sensors, and sophisticated analytics powered by artificial intelligence, thus optimizing the timing of maintenance interventions and significantly enhancing operational reliability and cost efficiency [1-3].

Bearings, as critical components in rotating machines, are prone to mechanical stress, wear, and thermal fatigue. Early fault signs often appear in vibration and temperature signals, making accurate, real-time monitoring essential for effective condition-based maintenance [4, 5].

Reliable experimental setups that simulate bearing degradation in controlled laboratory environments are becoming more and more important for developing, validating, and refining predictive maintenance methodologies [4]. The BTS-P3000 simulator enables realistic degradation experiments under controlled conditions, supporting systematic evaluation of prognostic techniques.

However, traditional setups often lack automation, robust data handling, and intuitive visualization. Manual acquisition and limited data management reduce repeatability and slow research progress [6]. To address these gaps, this paper presents an upgraded BTS-P3000 system that integrates high-resolution data acquisition with a modular web-based application.

The platform includes a LabJack T7 Pro device for real-time multi-sensor monitoring and a software stack based on FastAPI and React for experiment control and visualization. It supports reliable, scalable data processing and offers a foundation for testing prognostic algorithms in rotating machinery diagnostics.

The key contributions of this research include:

- Development of an automated and reliable Data Acquisition: Eliminating manual interventions, ensuring consistent and high-quality sensor data collection.
- Structuring efficient Data Storage: Employing optimized data formats, such as Apache Parquet [7], enabling effective retrieval and advanced analytics.
- Deploying Interactive Visualization: Providing intuitive dashboards and immediate monitoring of bearing conditions, significantly enhancing experimental diagnostics.

As a result, this research contributes meaningfully to predictive maintenance by improving the efficiency, repeatability, and diagnostic capabilities of laboratory experiments, aligning closely with modern trends in Industry 4.0 predictive maintenance research.

The paper is structured as follows: Chapter 2 provides a detailed overview of the system architecture. Chapter 3 describes the experimental setup and procedure. Chapter 4 presents and discusses experimental results, while Chapter 5 summarizes conclusions and suggests future research.

2 SYSTEM ARTHITECTURE

This chapter provides an overview of the detailed system design, including the overall architecture, selected technologies, and critical system components. The primary aim of the system design is to ensure effective real-time data acquisition, robust storage, scalable software architecture, and intuitive visualization capabilities. The implemented design ensures modularity, flexibility, scalability, and ease of maintenance, which tends to be the key characteristics for modern laboratory or industrial systems.

2.1 System Architecture Overview

The system follows a modular architecture composed of five integrated components: a user interface (frontend), a backend service, a relational database, a high-efficiency data repository, and industrial data acquisition hardware (LabJack

T7 Pro). The components communicate through RESTful APIs, enabling synchronized operation and flexible scalability.

Fig. 1 illustrates the high-level system design, where the user interface (React) enables experiment configuration and monitoring; the backend (FastAPI) manages data streams and business logic; the MySQL database stores experiment metadata and configurations; the Parquet-based repository logs high-frequency sensor data; and the LabJack T7 Pro ensures precise multi-channel acquisition. The backend is built on asynchronous FastAPI endpoints capable of handling concurrent API calls and continuous data ingestion. Sensor data includes vibration (AIN1), temperature (AIN2), RPM (AIN0), and axial/radial loads (AIN3, AIN4), acquired at sampling rates between 5000 and 8000 Hz. These are logged locally and transmitted to backend services in configurable intervals (~5 seconds) for structured storage.

While the current system focuses on real-time data capture and visualization, it is also designed to support future integration of prognostic algorithms (e.g., signal-based classifiers or ML models) for online degradation analysis.

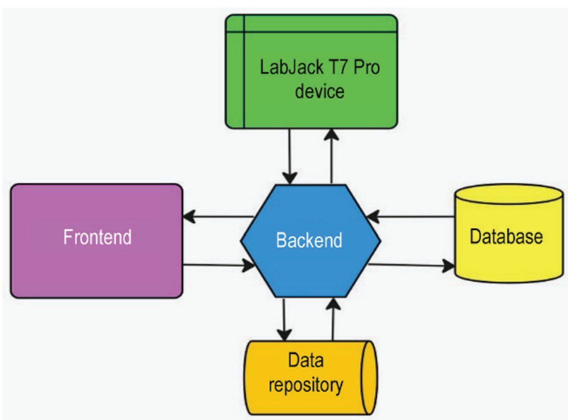

Figure 1 Modular architecture showing component interconnections, sensor data flow (AIN0–AIN4), acquisition frequency (5–8 kHz), and backend interfaces for real-time logging and experiment control

2.2 Functional Components of the Developed System

Each component within the modular architecture has clearly defined responsibilities, ensuring smooth and efficient system operations:

- **User Interface (Frontend - React):** Enables experiment configuration, live data visualization, and result analysis. Modular component design supports easy extension and future integration of diagnostic tools.
- **Backend (FastAPI):** Manages asynchronous data ingestion, experiment control, and communication with storage layers. Includes endpoints for configuration, data streaming, and metadata access.
- **Database (MySQL):** Stores structured experiment data, including sensor mappings, user-defined parameters, and system logs. Ensures transactional integrity and supports analytics queries.
- **Data Repository (Parquet-based storage):** Captures raw sensor data in compressed columnar format, optimized for high-speed access and batch analysis. Data is stored by experiment ID and sensor channel.
- **Data Acquisition Hardware Integration (LabJack T7 Pro):** Supports real-time, multi-channel data capture (analog/digital), Wi-Fi communication, and local SD logging. Sensors include accelerometers (vibration), thermocouples (temperature), and load cells.

2.3 Sequence of System Operations

The developed system follows a clearly defined operational workflow:

1) **Device Setup and Experiment Configuration:** Users configure device settings (sensor channels, calibration parameters, scan rate, etc.) via the React frontend. These settings are communicated to the backend via REST API endpoints, and the configuration parameters are stored securely in the MySQL database.
2) **Real-Time Data Collection:** Upon experiment initiation, the FastAPI backend initiates data collection via the LabJack T7 Pro device, continuously acquiring sensor data at predefined sampling rates and configurations. Collected raw data is temporarily stored locally on the hardware before transferring to the backend system.
3) **Data Transfer and Storage:** Real-time collected sensor data is systematically transferred from the LabJack T7 Pro device to the backend, where it is immediately stored in the Parquet-based repository, ensuring efficient long-term storage and rapid analytical accessibility.
4) **Data Visualization and Analysis:** Once data acquisition is completed, the React frontend retrieves experimental data through the backend APIs, presenting intuitive, interactive visualizations. Users can examine detailed graphical trends, analyze experiment parameters, export data (e.g., in CSV format), and conduct comprehensive data-driven diagnostics for maintenance decisions.

The sequential interaction between system components is illustrated in Fig. 2, which outlines the end-to-end workflow from device setup to final experiment result visualization.

Figure 2 Sequential workflow of system operations

2.4 Key System Features and Scalability

The developed system exhibits several features that contribute to its robustness and adaptability for diverse predictive maintenance scenarios:

- **Scalability:** The modularity of the architecture facilitates straightforward expansion, enabling the inclusion of additional sensors, data streams, or analytical capabilities without significant redesign.
- **Robustness:** Technologies such as FastAPI and React provide performance and reliability, especially under conditions requiring high concurrency and real-time responsiveness.
- **Flexibility:** Users can dynamically adapt system configurations (sensor channels, scan rates, and

experiment parameters), catering to various experimental and industrial needs.
- **Data Integrity and Security:** Consistent data integrity across transactions is maintained through MySQL's relational model and ACID properties, ensuring reliable and secure data storage.
- **Efficient Data Management:** Parquet storage optimizes sensor data compression and retrieval performance, crucial for handling vast datasets generated in long-term experiments.

3 EXPERIMENTAL SETUP

This chapter describes the experimental setup used to validate the effectiveness of the developed system for accelerated bearing degradation testing. The setup includes the description of the hardware components, their configuration, data acquisition procedures, as well as the integration with the developed software application. The experimental procedures were carefully designed to closely simulate real industrial conditions, thereby enabling thorough validation and accurate assessment of the system's performance.

3.1 Prognostic Bearing Test Simulator (BTS-P3000)

The core experimental apparatus used in this research was the Bearing Test Simulator BTS-P3000, as shown in Fig. 3. The BTS-P3000 is specifically designed for performing accelerated bearing degradation experiments by simulating realistic conditions of load, speed, and temperature, closely resembling those encountered in industrial environments. The main purpose of the simulator is to induce controlled bearing failures through accelerated degradation, allowing comprehensive study and validation of predictive maintenance strategies.

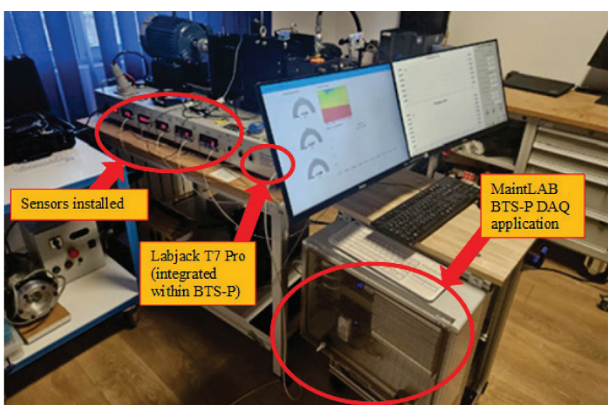

Figure 3 BTS-P3000 simulator after system upgrade

The BTS-P3000 provides the following key functionalities:
- Precise control over rotational speed (RPM), axial, and radial loading.
- Adjustable test parameters including temperature monitoring capabilities.
- Capability of running continuous or intermittent test cycles.
- Designed for durability and repeatability under extended testing conditions.

3.2 Data Acquisition Hardware

Data collection within the experimental framework was performed using the industrial-grade LabJack T7 Pro data acquisition device. The T7 Pro, depicted in Fig. 4.

Figure 4 LabJack T7 Pro

The main characteristics that influenced its selection for this research include:
- 14 Analog Inputs (up to 24-bit resolution via Sigma-Delta ADC).
- Digital I/O channels for auxiliary sensor integration.
- Integrated Wi-Fi connectivity for seamless communication and remote operation.
- Local data logging capability using microSD card, enabling secure and uninterrupted data storage.

Integration of the LabJack T7 Pro allowed continuous real-time data acquisition from multiple sensors, thus providing comprehensive monitoring of all relevant experimental parameters such as vibration, temperature, and loading forces.

3.3 Sensor Configuration and Measurement Parameters

The BTS-P3000 simulator was equipped with multiple sensors for real-time monitoring of critical parameters during degradation experiments.

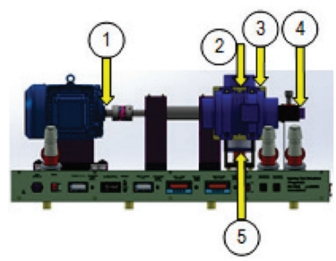

Figure 5 Schematic layout of sensor locations on the BTS-P3000 simulator for bearing fault analysis

The layout in Fig. 5 shows the physical positions of sensors: accelerometer sensor near the bearing housing (2), temperature sensor on the housing surface (3), speed sensor on the rotating shaft (1), and load cells at vertical (5) and axial (4) force application points, forming a comprehensive dataset for subsequent analysis.

3.4 Software Integration and Data Management

The developed hardware-software system integrates the DAQ hardware with a custom web-based application for device configuration, data collection, and visualization. Sensor channels were configured through the user interface, allowing adjustment of sample rates, calibration coefficients, and scaling parameters. During experiments, developed application enables LabJack T7 Pro monitoring while continuously recording data at predefined and front-end changeable rates and storing it locally.

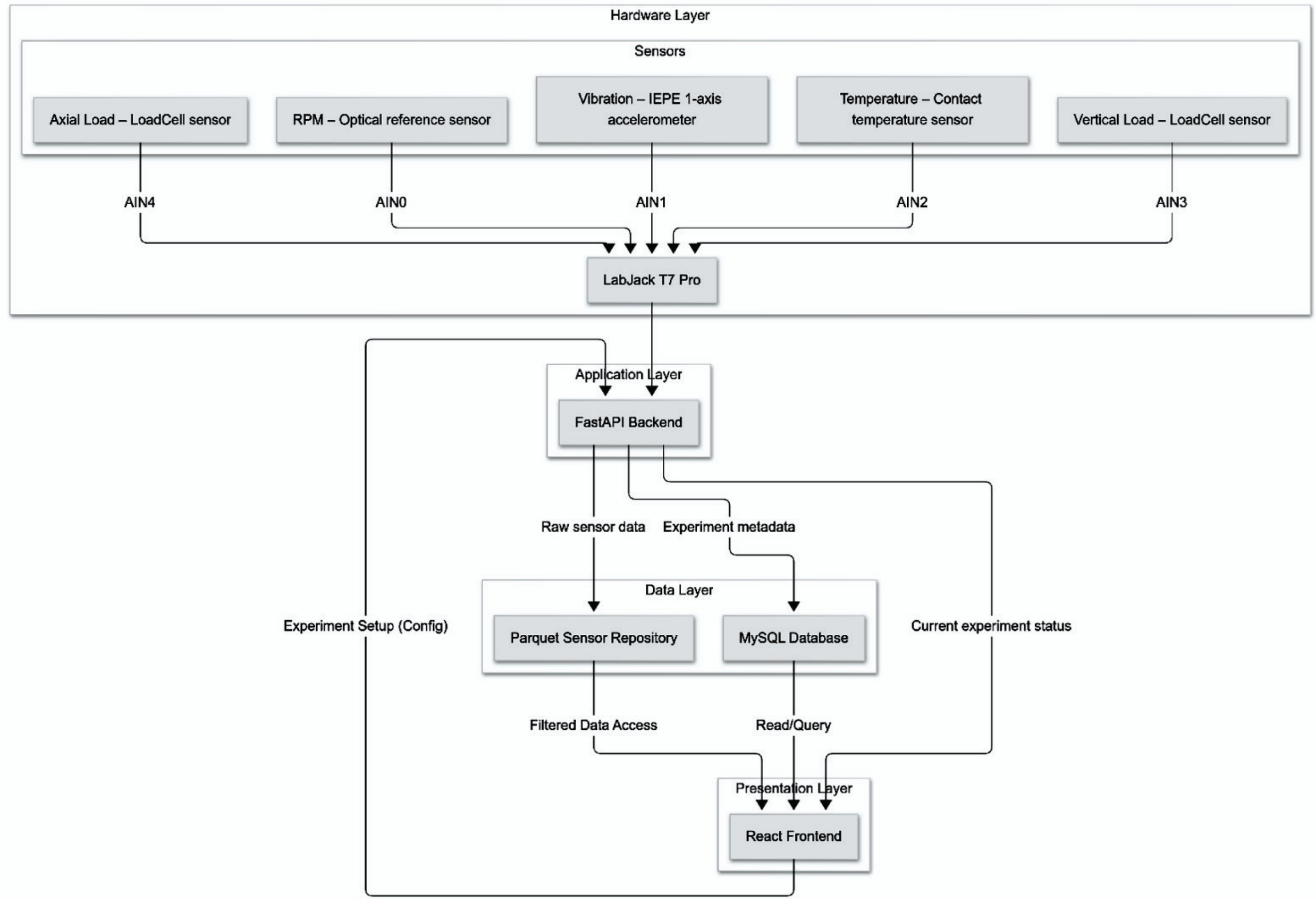

Figure 6 Layered software-hardware architecture of the developed bearing test simulator system

Fig. 6 illustrates the modular layered architecture of the extended BTS-P3000 system, structured into four functional layers: Presentation, Application, Data, and Hardware. The Presentation Layer includes the React-based frontend for experiment configuration and data visualization. The Application Layer features the FastAPI backend responsible for real-time data ingestion and control. The Data Layer comprises a relational MySQL database for experiment metadata and a Parquet-based repository for high-frequency sensor data. The Hardware Layer contains the LabJack T7 Pro acquisition device and five connected sensors: AIN0 – RPM (optical sensor), AIN1 – vibration (IEPE accelerometer), AIN2 – housing temperature (contact sensor), AIN3 – vertical load (load cell), and AIN4 – axial load (load cell). Bidirectional communication between layers enables full-cycle experiment execution, data logging, and on-demand access for visualization or export.

3.5 Experimental Procedure and Conditions

To comprehensively evaluate the system's capability, several experimental runs were conducted, each under different operational settings:

- **Variation of Scan Rates:** Experiments were performed at different scan rates to analyse the system's ability to accurately collect high-frequency data without data loss or distortion. Scan rates were carefully adjusted following manufacturer recommendations, typically ranging from 5000 to 8000 scans per second, ensuring optimal performance and avoiding system overload.
- **Controlled Operating Conditions:** Each experiment involved varying levels of axial and radial loads and speed settings. These controlled variations allowed assessment of the system's robustness and accuracy in handling diverse and dynamic operating scenarios.
- **Real-Time Monitoring:** Throughout each experiment, real-time data visualization was utilized to actively monitor sensor signals. The developed web-based application facilitated instant decision-making and troubleshooting, allowing immediate adjustments in test parameters if anomalies were detected.

3.6 Validation and Repeatability of Experimental Results

Experimental validation involved repeating the tests multiple times under identical conditions to ensure repeatability and consistency of collected data. This approach verified the system's stability and reliability. Data repeatability was confirmed by consistently obtaining similar sensor signals across multiple experimental runs under the same testing conditions, demonstrating the robustness and precision of the measurement system.

4 RESULTS AND DISCUSSION

Following the successful deployment of the MaintLAB BTS-P DAQ web application in a laboratory environment, a series of experiments were conducted to validate the system's functionality and the quality of collected data. The aim was to ensure that the application effectively manages device data acquisition, storage, and visualization under varying experimental conditions. This chapter presents the collected results, organized by experiment ID, and offers an objective analysis of the system's performance and signal consistency.

4.1 Overview of Measured Experiments

Six experiments were conducted to assess the system under different scan rate configurations. These experiments varied primarily by scan rate and active sensor conditions, allowing for comparative observation. Detailed analysis is focused on experiments ID 1 and ID 5, which were conducted at different scan rate configurations and provide representative examples of system behaviour under low and high data acquisition conditions.

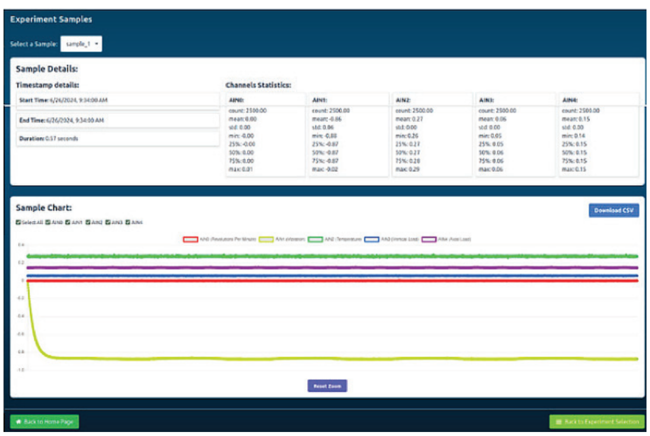

Figure 7 Detailed result view for Experiment ID 1

4.2 Experiment ID 1 – Lower Scan Rate Conditions

Experiment ID 1 was performed at a configured scan rate of 5000 scans per second. However, in accordance with LabJack T7 Pro documentation, the scan rate was automatically halved at the hardware level to avoid data overflow and ensure system stability. This is standard and not a result of any software limitation.

Fig. 7 shows the experimental detail screen within the application for Experiment ID 1. A consistent transient drop in vibration values (AIN1) was observed at the beginning of each measurement cycle, followed by signal stabilization. This pattern was confirmed by reviewing the exported CSV file, which contains raw measurement data for further analysis.

4.3 Experiment ID 5 – Higher Scan Rate Conditions

Experiment ID 5 was conducted using a scan rate setting of 8000 scans per second, again halved by the hardware to ensure optimal performance. Unlike the previous test, this experiment was carried out with the bearing test simulator fully active, exposing the system to increased signal dynamics.

4.4 Key Observations

An analysis of the experimental results identified specific signal deviations in two sensor channels: AIN1 (Vibration) and AIN4 (Axial Load). These channels displayed consistent anomalies across experiments, while other parameters such as AIN0 (RPM), AIN2 (Temperature), and AIN3 (Radial Load) remained within expected ranges and were correctly managed via configurable offsets and scaling in the device setup form.

Tab. 1 provides a summary of average values recorded for the most notable parameters based on visual inspection and CSV exports.

Table 1 Summary of key signal deviations for AIN1 and AIN4

Parameter	Expected Value	Observed Behavior	Remarks
AIN1 – Vibration	~Stable after init.	Transient drop at start	Possibly due to signal dynamics or sensor delay
AIN4 – Axial Load	~0.1 (no load)	~0.15 (persistent offset)	Likely calibration or sensitivity-related issue

These findings highlight the system's ability to consistently capture sensor data while also emphasizing the importance of calibration and signal stabilization during data collection.

4.5 Discussion and Recommendations

While the developed MaintLAB BTS-P DAQ system demonstrated reliable performance in data acquisition and visualization, several improvement areas were identified:

- **Vibration Signal Transients (AIN1):** The recurring drop at measurement start may be linked to sensor warm-up, mechanical dynamics, or signal latency. Future experiments should consider a brief buffer window before official data collection begins.
- **Axial Load Offset (AIN4):** A consistent elevation in expected zero-load values suggests the need for more precise calibration protocols. Revisiting sensor sensitivity and performing automated pre-experiment calibration routines may improve accuracy.
- **Software Stability:** Despite sensor-level discrepancies, the web application operated reliably across all experiments. System anomalies were hardware-related and not reflective of any backend or frontend software failure.
- **Future Integration:** Expanding the platform to incorporate additional sensor types (e.g., ultrasonic), real-time data streams, and advanced user interface

customization will further enhance the application's capabilities for industrial-scale predictive maintenance.

When comparing the developed system to existing experimental platforms, it is important to highlight key conceptual differences. The Case Western Reserve University bearing data center platform [13] is widely used for classification-focused research, offering standardized fault datasets suitable for machine learning benchmarking. In contrast, the primary goal of our system is to support prognostic modeling through controlled, long-term degradation experiments with adjustable operating conditions.

Furthermore, compared to PRONOSTIA [14], which is another reference platform for accelerated degradation studies, the BTS-P3000 simulator offers significantly higher mechanical flexibility. While PRONOSTIA employs a compact and constrained physical testbed, our platform allows broader variation in axial and radial loading, speed profiles, and sensor configuration, thereby enabling richer datasets for remaining useful life (RUL) estimation and model training.

5 CONCLUSION AND FUTURE WORK

This paper presented the development and validation of an extended prognostic bearing test simulator that integrates industrial-grade data acquisition hardware with a modular, web-based software application for monitoring and analysis that advances the capabilities of laboratory-based predictive maintenance research. By combining high-resolution data acquisition, structured analytics, and user-centric design

Future work will focus on three strategic directions. First, the integration of additional sensing modalities, such as ultrasonic sensors, would enrich the diagnostic context and improve fault detection coverage. Second, enhancing real-time visualization and enabling live anomaly detection can further support proactive decision-making. Third, automated sensor calibration routines, including dynamic offset and scaling adjustments, are essential to ensure measurement accuracy and repeatability, especially in long-term degradation studies.

In conclusion, the developed system advances the capabilities of laboratory-based predictive maintenance research. By combining high-resolution data acquisition, structured analytics, and user-centric design, it provides a foundation for scalable and reliable experimentation, as well as a promising platform for future extensions into real-world industrial applications.

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6 REFERENCES

[1] Ucar, A., Karakose, M., & Kırımça, N. (2024). Artificial intelligence for predictive maintenance applications: Key components, trustworthiness, and future trends. *Applied Sciences, 14*(2), 898. https://doi.org/10.3390/app14020898

[2] Murtaza, A. A., et al. (2024). Paradigm shift for predictive maintenance and condition monitoring from Industry 4.0 to Industry 5.0: A systematic review, challenges, and case study. *Results in Engineering, 24*, 102935. https://doi.org/10.1016/j.rineng.2024.102935

[3] Abdelillah, F. M., et al. (2023). Hybrid framework for predictive maintenance based on data and knowledge in the context of Industry 4.0. In *Proceedings of the International Conference on Model and Data Engineering* (pp. 1-7). Springer Nature Switzerland.

[4] Kolar, D., et al. (2020). Fault diagnosis of rotary machines using deep convolutional neural network with wide three-axis vibration signal input. *Sensors, 20*(14), 4017. https://doi.org/10.3390/s20144017

[5] Kolar, D., et al. (2021). Intelligent fault diagnosis of rotary machinery by convolutional neural network with automatic hyper-parameters tuning using Bayesian optimization. *Sensors, 21*(7), 2411. https://doi.org/10.3390/s21072411

[6] Mišković, K. (2025). Upgrade of the laboratory system for the accelerated degradation of the state of the bearings with a computer system for data collection and processing. *Graduation thesis*. https://urn.nsk.hr/urn:nbn:hr:235:124216

[7] Apache Parquet Project. (n.d.). *Apache Parquet documentation*. The Apache Software Foundation. Available at: https://parquet.apache.org/docs/

[8] Harper, K. E., & Dagnino, A. (2014). Agile software architecture in advanced data analytics. In *2014 IEEE/IFIP Conference on Software Architecture* (pp. 243–246). https://doi.org/10.1109/WICSA.2014.16

[9] Subramanian, S. (2017). A review on web application testing and its current research directions. *ResearchGate*. https://doi.org/10.11591/ijece.v7i4.pp2132-2141

[10] Jaleel, H. Q. (2019). Testing web applications. *SSRG International Journal of Computer Science and Engineering, 6*(12), 1-9. https://doi.org/10.14445/23488387/IJCSE-V6I12P101

[11] Dhore, P., et al. (2023). A brief overview of various approaches and procedures in manual software testing. *Journal of Pharmaceutical Negative Results*, 455-464.

[12] Mezmir, E. A. (2020). Qualitative data analysis: Overview of data reduction, data display, and interpretation. *Research in Humanities and Social Sciences, 10*(21), 15-27.

[13] Case Western Reserve University Bearing Data Center. (n.d.). https://engineering.case.edu/bearingdatacenter

[14] Nectoux, P., Gouriveau, R., Medjaher, K., Ramasso, E., Chebel-Morello, B., Zerhouni, N., & Varnier, C. (2012). PRONOSTIA: An experimental platform for bearings accelerated degradation tests. In *Proceedings of the Conference on Prognostics and Health Management* (pp. 1-8).

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Sustainability in Drone Technology – Tracking Using Drone

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Abstract: Sustainability and Industry 4.0 technologies are increasingly integrated into modern production. Among these, drones represent a newer autonomous device with potential beyond aerial photography. This paper introduces a novel industrial application of drones: inventory checks and tracking of Autonomous Mobile Robots (AMRs). At the University of Miskolc's Logistics 4.0 Laboratory in Hungary, a roller conveyor system transports unit loads, supported by one larger AGV (Automated Guided Vehicle) and two smaller AMRs. While these ground-based devices navigate independently, their sensing is limited to ground level. The proposed drone solution enhances this system by performing horizontal photographic inventory checks and tracking the movement of mobile robots from above. This dual-purpose use of a single drone improves motion accuracy and reduces the need for multiple tracking systems. The paper outlines the system's design and presents the results of implementing this drone-supported approach.

Keywords: Autonomous Mobile Robot (AMR); drone; inventory check; logistics; sustainability; tracking

1 INTRODUCTION

Nowadays, sustainability and Industry 4.0 technologies are widely referred to in production and management of technology. One of the Industry 4.0 technologies is autonomous devices, and among them, drones represent one of the newest advancements, alongside older robotic technologies. Drones are commonly used in everyday life for aerial photography; however, in industry, this capability can be utilized in various ways.

This paper proposes a new approach to the industrial application of drones. The idea is to use a drone for inventory check and also tracking an AGV (Automated Guided Vehicle) or AMR (Autonomous Mobile Robot). At the University of Miskolc in Hungary, within the Laboratory of Logistics 4.0, a roller conveyor system is in place that can transport unit loads along different routes. For performing storage, an automated shelving system was implemented into the laboratory. Substituting manual transport, the system incorporates one larger AGV and two smaller AMRs. The AGV carries unit loads, while the AMRs assist in predicting and optimizing the AGV's route. Although these devices utilize their own navigation systems, they are limited to sensing objects at ground level. By employing a drone to track these units from an overhead photographic perspective, motion accuracy can be improved, and a single device is sufficient for this purpose. From other perspectives, with the front photography view the same drone can be used also for inventory check and scanning.

This paper presents the background of this function and explores different results. Chapter 2 discusses the literature background of this topic. Chapter 3 introduces the background for inventory check, while Chapter 4 presents the steps taken in its development so far. Chapter 5 highlights the practical implementation of inventory check and tracking mobile devices. Finally, Chapter 6 summarizes the paper and shortly enhances future possibilities.

2 LITERATURE BACKGROUND

The integration of Industry 4.0 technologies in manufacturing and logistics has been widely researched in recent years. Sustainability and automation are central themes, with autonomous systems such as drones playing a crucial role in industrial applications.

A key aspect of Industry 4.0 is the improvement of logistics operations through automation and digitalization. According to Zhong et al. [1], smart manufacturing uses autonomous devices to optimize efficiency and reduce human operation. Drones, as a part of these technologies, have gained attention for their potential in logistics. Researchers such as Otto et al. [2] highlight their role in inventory monitoring and real-time data collection.

In warehouse management, drones have been increasingly used for automated inventory tracking, as reported by Kim and Lee [3]. Their study demonstrates how aerial imagery and machine learning algorithms can improve stock accuracy and reduce operational downtime. Furthermore, drones have been proposed as a solution for supporting Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs). According to Bogue [4], AGVs and AMRs rely primarily on ground-based navigation sensors, which limit their awareness of overhead obstacles and global positioning accuracy.

Recent studies suggest that drones can complement AGVs and AMRs by providing aerial tracking and guidance. Eski and Tjahjono [5] argue that integrating drones with existing robotic systems improves operational flexibility and safety. This is coincidence with experimental implementations at the University of Miskolc's Logistics 4.0 laboratory, where a drone is tested for improving AGV/AMR path accuracy and collision avoidance.

Additionally, the role of artificial intelligence (AI) in drone navigation has gained interest. Advanced AI-driven systems allow drones to adapt to dynamic environments, improving their tracking and decision-making capabilities. Researchers such as Smith and Brown [6] suggest that integrating AI with drone navigation can significantly enhance performance by enabling real-time adjustments based on environmental factors. This is particularly important in industrial settings where obstacles and workflow variations occur frequently.

Another important area of research is the communication and data exchange between drones and AGVs/AMRs. Wireless sensor networks have been explored to create smooth communication, as written by Chang et al. [7]. Their study highlights how reliable data transmission between aerial and ground-based autonomous devices can improve coordination and reduce errors in logistics operations.

Further advancements in sensor technology, including LiDAR and thermal imaging, have also been explored to enhance drone-assisted tracking. Johnson et al. [8] investigated how combining multiple sensors can improve localization accuracy and overall efficiency in industrial environments.

The current framework of research highlights the potential of drone-robot integration in industrial automation. Future studies should explore advanced sensor fusion techniques and artificial intelligence applications to maximize efficiency and reliability. Moreover, energy efficiency remains a challenge in drone-based tracking, as highlighted by Wang et al. [9]. Addressing battery life and optimizing energy consumption are crucial for long-term industrial deployment.

3 BACKGROUND OF INVENTORY MANAGEMENT WITH DRONE TECHNOLOGY

Inventory management plays a crucial role in a company's operations, as it is essential to accurately track the quantity and location of all materials in the warehouse. Proper inventory records are necessary for forecasting, which is essential for order management. Orders must be executed based on inventory levels to prevent supply chain disruptions.

Figure 1 Drone in a warehouse [10]

In larger warehouses, the inventory inspection process can be time-consuming and may also lead to higher costs. Therefore, drone-assisted inspection is compared with traditional methods, as time savings are one of the most important factors in achieving efficient operations.

An example of using drones in a warehouse is illustrated in Fig. 1. In this case there was a bigger and older drone available, which can be controlled basically manually or semi-automatically, the fully automated movement can be performed only in a limited way. Hence at the background of picture a drone operator can be seen with a controller and a mounted smartphone for checking the movement of drone.

3.1 Conditions

The use of drones in inventory management offers several advantages, such as enabling full automation of the process, thereby minimizing inventory discrepancies caused by human error. However, certain essential conditions must be met to ensure the smooth and efficient implementation of this process.

3.1.1 Essential Requirements for Drone Implementation

First and foremost, it is necessary to acquire a drone that can be equipped with various sensors or cameras to read barcodes, QR codes, or RFID tags. Precise navigation is crucial, as even a few millimeters can determine whether a collision occurs or is successfully avoided.

Additionally, the drone must be capable of highly accurate maneuvering since it needs to be navigated between shelves. If it lacks sufficient precision, it would be unable to travel effectively from one shelf to another, making it essential to ensure that the selected drone possesses exceptional maneuverability and control. Therefore cost-effective, toy-like drones are not proper for this purpose.

3.1.2 Navigation

Indoor navigation can be challenging when using GPS, as its functionality may be compromised in enclosed spaces. To ensure effective navigation in such environments, an appropriate localization system must be implemented. GPS-based localization has several weaknesses. Since it relies on radio signals, it is susceptible to interference from various sources. In certain environments, such as areas surrounded by tall buildings, GPS signals may be unavailable, rendering these locations GPS-deprived zones. Even when a drone has a direct line of sight to GPS satellites, its signal information can be manipulated by malicious attackers. As a result, GPS-based navigation can accumulate positioning errors, leading to inaccurate navigation in many cases.

In study, Emimi et. al. [11] proposed a system for autonomous path following that utilizes visual information captured by a monocular camera mounted on the drone. The advantage of this approach is that the information is immediately available, does not depend on external signals, and is less vulnerable to spoofing attacks. The proposed system builds a combined database using simulator-generated data as well as data collected from manually controlled or GPS-based navigation paths. This database is then used to train a Convolutional Neural Network, which generates drone control commands based on detected images, thereby enabling autonomous drone navigation.

3.1.3 Data Processing

Also, data processing software is a key factor that can process drone-scanned 1D ID codes, QR codes and RFID tags in real time and link this data to the warehouse's inventory management system. In order to communicate with the company's inventory management system, the drone requires wireless connectivity and device compatibility.

3.1.4 Safety

Safety measures must be observed to minimize both personal injury and material damage. When using a drone, the drone must be given adequate space to avoid accidents and therefore be safe. Designating flight zones and communicating them to workers can make it easier to ensure that the drone's path is not crossed by humans. Regular, professional maintenance of the drone can prevent malfunctions and resulting accidents.

3.1.5 Warehouse Design

The warehouse must be arranged and designed in such a way that the drone has easy access to the labels identifying the products on the shelves. This also means that the rows between shelves must have sufficient width to allow maneuvering, including that the labels on the products or materials on the shelves are in a position that can be read by the drone's camera or code reader. Therefore, the label must be facing the right direction, and its visibility is also important, which can be ensured by the lighting in the warehouse or by an auxiliary light source mounted on the drone.

3.1.6 Identification System

The company needs to implement and use an identification system that can interpret and manage separate tags such as barcodes or QR codes. The absence of such an identification system and the inadequate handling of drone-read codes would limit the transparency of the stock control system.

3.1.7 Operator

To ensure that everything runs smoothly, the drone operator needs to have the right knowledge to operate the drone and to use the software, which may require training, and for bigger drone, also a so-called drone license. Maintenance is also important in a case like this, as a drone malfunction can mean a big loss of time, especially if the maintenance worker is unable to correct the fault after the malfunction has occurred due to lack of knowledge, or even if he or she makes the situation worse, like making an accident, especially critically to humans.

3.1.8 Costs

Costs should be calculated at every step of the system's implementation, sometimes more, sometimes less. Setting up a warehouse or converting an existing warehouse, purchasing a drone, purchasing software for identification, all involve significant costs. Attention must also be paid to ensuring data security and protection, as the information collected by the drone must be handled with care, so security systems may need to be put in place. Furthermore, there are costs associated with the purchase of maintenance equipment or spare parts, which are necessary for regular use, as wear and tear and possible failure are inevitable. What can increase expenditure even further is the amounts spent on employee training.

3.2 Example for Inventory Management with a Drone

There are companies where it is possible to register stocks by drone. In [12], Tubis et al. tested a drone-based inventory tracking system at a logistics service provider's decentralized center in Poland was investigated. The drone used included a proximity sensor, gyroscope, camera and GPS receiver. In this case, it was not possible to control the drone via GPS positioning, as there was no GPS signal in the warehouse under investigation. Therefore, positioning was only possible by tracking the drone's movements. The unit loads placed on the shelves of the shelving system used had a QR code identifier, which is identified and interpreted by the system. It is solved by stopping the drone after finding it and generating the streamed image stream that can be interpreted by the scanner software of the handling device.

3.3 QR Code and Barcode

When building a new system, it is necessary to decide whether to use a barcode or another code, such as a QR code. However, if a modification of an existing system is the goal, it is needed to consider whether to use the existing one or introduce a different code type, as both have their advantages and disadvantages.

3.3.1 Barcode

This type of ID code can store up to 20 characters of data, taking up more space than a QR code. If a barcode becomes corrupted it can no longer be scanned, and the position of the barcode is also phonetic, cannot be any, as by the QR-code.

3.3.2 QR Code

A QR code can store up to 7100 characters of data in both vertical and horizontal directions. If a QR code is damaged, it can recover about 30-35% of the data. Its position is less important because it can be scanned in multiple orientation, it is not as bound in this space as a barcode, and it stores the same amount of data in a tenth of the area [13].

4 PRACTICAL IMPLEMENTATION OF INVENTORY CHECK

The next measurement was carried out at the University of Miskolc, in the Laboratory of Logistics 4.0 in the Institute of Logistics. The purpose of the measurement was to compare, through a practical example, the inventory check is more efficient either with a drone or with a traditional manual barcode scanner. The drone was controlled manually, so a more inaccurate result will be presented.

4.1 Used Tools for Practical Measurement

The instruments used during the measurement process are firstly described in this subchapter, especially the drone, the handheld barcode scanner, and the shelving system under evaluation. Additionally, during manual barcoding, an elevation aid was required to access the upper shelves, since the top shelf is positioned at a considerable height. In this case, a simple chair was used for this purpose.

4.1.1 Drone

The drone used was from brand DJI and type Mini 4 Pro, as shown in Fig. 2a. The DJI Mini 4 Pro is a drone that weighs less than 249 grams and is easy to carry due to its small size. This drone is C0 certified, which means it has a maximum take-off weight of 0.25 kg, a maximum flight speed of 19 m/s and a flight altitude limited to 120 m. Its camera is capable of 4K resolution, HDR (High Dynamic Range) vertical recording and video transmission in Full HD quality up to a distance of 20 km. It is equipped with omnidirectional obstacle detection, which makes it easier to handle, as using it means that it avoids hitting obstacles on its own. In active use, the manufacturer's battery life is 34 minutes [14, 15].

(a) DJI Mini 4 Pro (b) Zebra TC20 with handle part

Figure 2 Drone and Scanning device (self-made photo)

4.1.2 Manual Barcode Scanner

The hand-held barcode scanner consists of two separate parts, a mobile data collector and a corresponding gun barcode scanner. Type of data collector Zebra TC20, as shown in Fig. 2b.

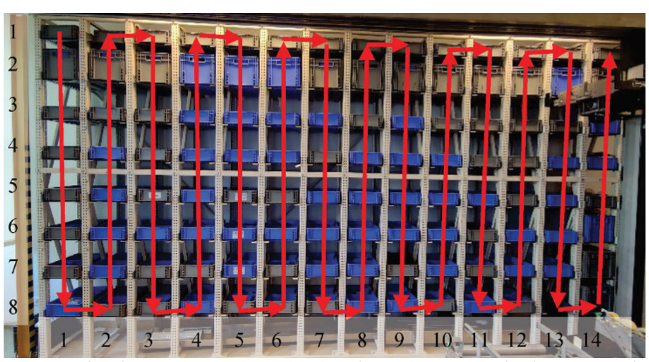

Figure 3 Shelf system with movement route for measurements (self-made photo)

4.1.3 Automated Shelving System

The shelving system consists of 14 columns and 8 rows (see Fig. 3), but as the load machine could not approach the highest and lowest rows due to the proximity of the ceiling and floor, hence the measurement was only performed technically along 6 rows.

4.2 Measurement Procedure

The measurement was started by using the drone. The first problem that arose was that the load machine in the lab was covering two poles in front of the drone, so it could not approach them. This reduced the possibility of going through the shelves row by row, as this would have required the drone to avoid the loading machine in each row, which is time consuming. Therefore, the column-by-column movement was chosen. Then the fact occurred that it would be more ideal if the drone started not on the columns from one direction, but first from the top to down, and then always start on the next column from where we ended on the previous column. The route of movement is illustrated on the Figure 3. However, this method is still issued due to the presence of the load machine. This problem was solved by moving the loader during the inspection, i.e., the drone was moved away from the shelf by the fifth column and then moving the load machine to the first column, so it was no longer in the way. The operation of inventory check then continued as drone approached the sixth column.

The next step involved the use of the traditional inventory control method. For this, the barcode scanner and the chair were required to access the higher shelves. To ensure a more accurate comparison, the shelving system was examined in the same sequence as before with the drone. However, it is important to note that the load machine also had to be repositioned in this process. The chair was first placed in front of the second column, and the first three columns were examined. It was then moved to the fifth column to inspect the next three columns. Following this, the load machine was relocated to the first column, and the process continued in groups of three columns until the final two columns were reached.

4.3 Comparison of Inventory Check Methods

The most important point of comparison is the time difference between the two methods of implementation.

4.3.1 Drone Method

From the very beginning of the measurement, it became clear that the drone could not be flown as close to the ground as would be necessary to read the bottom line. If this method is to be implemented in an existing warehouse, it is essential to consider that the shelving system may not always be optimally designed. In such cases, either a reconfiguration of the layout or the integration of multiple methods may be required, depending on the most cost-effective solution. However, if the goal is to utilize the drone in a newly constructed warehouse rather than replacing an existing system, the design must ensure that the drone can maintain a safe distance from surrounding objects during flight, with no obstacles obstructing takeoff or landing. Additionally, a dedicated charging station is necessary, as the drone will require periodic recharging, which must be factored into the warehouse layout. Pathways between the shelves and the charging station should also be planned to enable efficient automation.

Before implementation, it is crucial to thoroughly examine the drone's specifications, including its sensors, cameras, and compatibility with the warehouse's internal structure. If the drone is operated manually rather than autonomously, human control will be required, though this approach is less efficient than full automation. Regardless of the mode of operation, a maintenance technician will be necessary to repair potential failures, along with the appropriate tools and replacement parts.

The following section outlines the methodology used to estimate the duration of automated operation. In the measurement process, the entire operation—from takeoff to landing—took 398 seconds under manual control. However, automation would significantly reduce this duration by eliminating the need for manual corrections caused by imprecise control inputs. Since the time required to travel between the charging station and the shelving system depends on the station's location, only the duration from the approach to the shelving system until the final barcode was scanned was considered, which amounted to 349 seconds.

The positioning times were categorized into horizontal and vertical movements, with the shortest recorded times for each category used in the calculations. The barcode reading time was assumed to be 0,5 seconds per scan. Throughout the experiment, the drone executed 70 vertical and 14 horizontal movements. The shortest and average time for a vertical adjustment was recorded at 0,89 and 1,735 seconds, respectively, while the shortest and average time for a horizontal movement was 1,67 and 3,0 seconds, respectively. However, one of the 14 horizontal movements required the drone to move away from the shelves to accommodate load machine repositioning, which took 50,89 seconds. For the remaining 13 horizontal movements, the shortest recorded time was used.

With these calculations, the total time required for 70 vertical adjustments incl. shortest time of 0,89 seconds, 13 standard horizontal movements incl. shortest time of 1,67 seconds, one extended horizontal repositioning, and 84 barcode scans amounted to 151,455 seconds. If, instead of the shortest times, the average movement durations were used — 1,735 seconds for vertical movements and 3,0 seconds for horizontal movements — the total estimated duration would be 202,53 seconds. Using shortest time has risks, such as necessity for drone movement correction, not exact location of barcodes.

4.3.2 Traditional Method

With this method, the same problem did not occur as in the other case of not being able to reach certain shelves because of the proximity to the ground, so access to the barcodes is easier in crowded places. However, moving the load machine was still necessary to reach all the barcodes. It took a total of 230 seconds to check the entire shelving system.

4.4 Comparing the Results

This subchapter discusses the limitations of the approaches used. From the times written above and summarized in Tab. 1, it can be seen that the drone method is only profitable if it is automated, since it takes more time with manual control than with the traditional inspection, based on these results. If the drone is automated, the inventory record time is significantly reduced, compared to when an operator controls the drone, which is also confirmed by the fact that the 349 seconds measured with manual control are less than two-thirds of the 202,53 seconds calculated with average values. The method is also depends on the storage system, because in a warehouse where the barcode of every product stored there can be read from the ground, the use of a drone is probably not significantly faster. The traditional method is slower for the higher the shelving system under examination, since the most time is required for the operator performing the inspection to move the ladder and stand on it, so the higher he has to go, the slower the operation will be. However, it must be also taken into account that every drone has a period of time after which it can no longer operate, so if it has to move over such a large area that it cannot do so without charging, it will mean a significant loss of time. Therefore, choosing the drone is also a key task in such a case. Choosing an inventory management method is a multifunctional task that requires careful and thorough research, as it depends on the quantity of products to be recorded, the design of the warehouse, the variety of type and size of products. The labor intensity is for manual control is continuously 1 person, for the automated drone control is 1 person, but only for setup. The drone should work off-hours.

Table 1 Comparing results

Testing method	Time (s)
Drone – measured manual control	398
Drone – calculated automated control	203
Traditional handheld control – measured	230

5 EXAMPLES FOR OTHER TRACKING FORM WITH A DRONE

This chapter shortly introduces two further examples.

5.1 Tracking a Unit Load with Drone

The first method is following a unit load from overhead photographic way. The unit load in this case moves onto the conveyor system, and the drone can follow its movement. The example is illustrated in the Fig. 4.

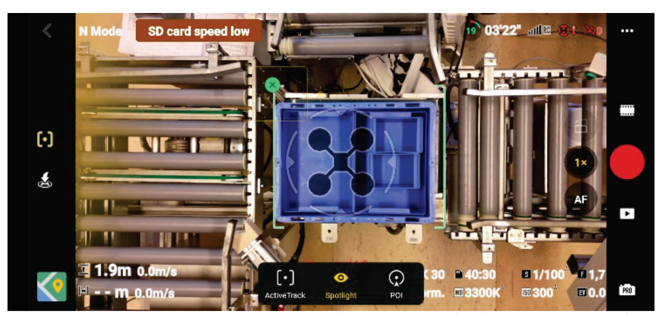

Figure 4 Tracking a unit load by drone from overhead (self-made screenshot)

5.2 Tracking an AMR with Drone

The other method is tracking movement of an AMR. This AMR is a Festo Robotino, which can be controlled either manually or automatically. In this way the drone determines the position of AMR using a vision system. Then the drone can send this data across the laboratory control to the AMR to correct its position. An example from the viewpoint of drone can be seen in Fig. 5.

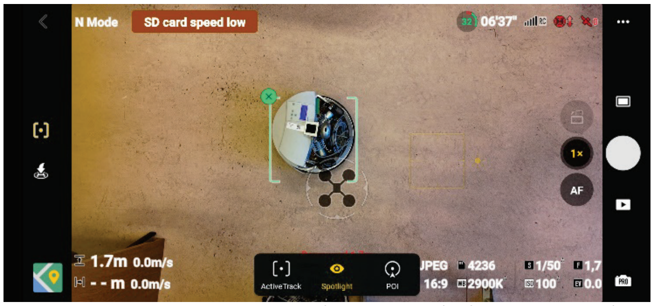

Figure 5 Tracking an AMR by drone from overhead (self-made screenshot)

6 SUMMARY

The paper dealt with different tracking methods using drone. After introduction, the background of tracking with drone technology was detailed. In the next part, practical implementation was written. The first goal was an inventory check, where the traditional handheld and the novel drone method was compared. It can be stated that a drone can be significantly faster, however it needs fully automatic operation and good located barcodes for improving sustainability factor. Two other examples for tracking with drone technology were shortly introduced due to lack of space. Here tracking of a unit load moving on conveyor system and tracking of an AMR were illustrated. Regarding future research directions, the tracking solutions can be improved including further enhancements in drone tracking accuracy, integration with AI-based predictive analytics, and the potential for multi-drone cooperation to optimize industrial automation processes.

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7 REFERENCES

[1] Zhong, R. Y., Xu, X., Klotz, E., & Newman, S. T. (2017). Intelligent manufacturing in the context of Industry 4.0: A review. *Engineering, 3*(5), 616–630. https://doi.org/10.1016/j.eng.2017.05.015

[2] Otto, A., Agatz, N., Campbell, J., Golden, B., & Pesch, E. (2018). Optimization approaches for drone delivery and logistics systems. *Transportation Science, 52*(4), 579–608.

[3] Kim, H., & Lee, J. (2019). Aerial inventory tracking using drone-based computer vision. *Computers in Industry, 109*, 77–87.

[4] Bogue, R. (2020). The role of drones in logistics: A review. *Industrial Robot, 47*(1), 33–38. https://doi.org/10.1108/IR-01-2020-0017

[5] Eski, S., & Tjahjono, B. (2021). Enhancing AGV navigation through drone assistance. *International Journal of Production Research, 59*(15), 4623–4639.

[6] Smith, J., & Brown, L. (2022). Artificial intelligence in drone navigation systems: A new frontier. *Automation Journal, 65*(2), 112–128.

[7] Chang, P., Lee, W., & Gomez, R. (2021). Wireless sensor networks for autonomous vehicle communication. *IEEE Transactions on Industrial Electronics, 68*(9), 7589–7601.

[8] Johnson, M., Patel, D., & Wang, Y. (2020). Sensor fusion techniques for industrial drone navigation. *Sensors and Actuators A: Physical, 315*, 112–125.

[9] Wang, X., Liu, Z., & Chen, Y. (2021). Energy-efficient drone operations for industrial applications. *Journal of Sustainable Robotics, 7*(4), 214–228.

[10] cargo-partner. (2025). Not everything that has wings is a drone. Or is it? https://www.cargo-partner.com/trendletter/issue-4/drones-in-warehouse-logistics

[11] Emimi, M., Khaleel, M., & Alkrash, A. (2023). The current opportunities and challenges in drone technology. International *Journal of Emerging Technologies and Innovative Research, 1*, 74–89.

[12] Tubis, A., Ryczyński, J., & Zurek, A. (2021). Risk assessment for the use of drones in warehouse operations in the first phase of introducing the service to the market. Sensors, 21(20), 6713. https://doi.org/10.3390/s21206713

[13] Mishra, A., & Mathuria, M. (2017). A review on QR code. *International Journal of Computer Applications, 164*(9), 17–19. https://doi.org/10.5120/ijca2017913739

[14] DJI. (2024). DJI Mini 4 Pro. https://www.dji.com/hu/mini-4-pro

[15] Pettke, G., Kozyro, W., Gałka, P., Trzeciak, G., & Wołejsza, P. (2021). Certification of unmanned aircraft (UA). *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 15*(1), 143–155. https://doi.org/10.12716/1001.15.01.14

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The Impact of Inventory Management Innovations on Industry 4.0 Manufacturing Strategies

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Abstract: In general, the goal of inventory management mechanisms is to develop inventory ordering rules that ensure optimal inventory levels. By "optimal inventory level," we mean a level where stock is always available when needed, while storage costs are minimized. To achieve this, a thorough understanding of inventory-related costs is essential for determining the economical level. In addition to classical and widely used inventory management mechanisms, many companies also employ mixed or hybrid inventory strategies, which are based on the combination of elements from different systems. In Industry 4.0 manufacturing, determining the inventory levels of raw materials and semi-finished products presents a significant challenge for logistics professionals. Developments in Logistics 4.0, as well as advanced hybrid inventory management mechanisms, can provide substantial support to professionals in optimizing inventory levels.

Keywords: logistics; Industry 4.0; inventory control

1 INTRODUCTION

The continuous advancement of industrial production and the increasing prevalence of digitalization are driving innovations aimed at enhancing supply chain efficiency. In the era of Industry 4.0, inventory management strategies are undergoing a significant transformation, with the primary objective of ensuring more flexible, cost-effective, and sustainable operations. Through intelligent systems, data analytics, and automation, companies can optimize their inventory management processes, minimize excess stock, and respond more swiftly to market fluctuations. Hybrid inventory mechanisms are a critical component of innovative inventory management, integrating elements of traditional push and pull strategies [1]. These models enable businesses to dynamically adjust their inventory levels in response to actual demand while leveraging the capabilities of automated forecasting and predictive analytics. Such approaches are particularly relevant to Industry 4.0 manufacturing strategies, especially in Make-to-Order (MTO) systems, where production is exclusively driven by incoming customer orders. This model significantly reduces warehousing costs and losses resulting from overproduction [2].

2 THE MAKE TO ORDER PRODUCTION SYSTEM

In the dynamically evolving field of modern manufacturing driven by Industry 4.0 principles, the make-to-order (MTO) production system has emerged as a strategic approach to meeting customer demands with increased efficiency and flexibility [3-5]. The MTO system is a manufacturing strategy in which products are produced based on specific customer orders rather than being manufactured in anticipation of future demand. This approach contrasts with traditional manufacturing models such as make-to-stock (MTS), where goods are produced based on forecasted demand. MTO enables a high degree of product customization to meet unique customer requirements [6]. Products must be tailored to individual specifications, offering a personalized experience for customers. Unlike MTS models, MTO minimizes the need for large inventories. Production begins only when an order is received, reducing excess inventory and associated storage costs. MTO provides greater flexibility in responding to changes in customer preferences and market trends [7].

Manufacturers can quickly adapt to fluctuations in demand, making this an agile approach.

2.1 The Advantages of Make-to-Order (MTO) Production

Innovative inventory management strategies have a significant impact on a company’s competitiveness and operational efficiency [8]. Production tailored to individual customer needs increases customer satisfaction and loyalty, as consumers receive products that precisely meet their expectations. This not only strengthens customer relationships but also ensures a stable market position for the company in the long run. By optimizing inventory management, companies can reduce excess stock, leading to cost savings while minimizing losses from obsolete products. Lower inventory levels also contribute to more efficient financial management, as capital is not tied up in unnecessary stock but can be utilized in other strategically important areas, such as innovation or development. The ability to quickly adapt to market changes is also a key factor in today’s dynamic business environment. Companies that can respond flexibly to demand fluctuations and introduce new products rapidly gain a competitive advantage. Therefore, innovative inventory management solutions not only result in cost reduction and more efficient operations but also contribute to sustainable growth and strengthening market position.

2.2 Challenges of Make-to-Order Production

In a modern manufacturing environment, producing customized products presents several challenges that can impact a company's operations and competitiveness. One of the most critical factors is manufacturing lead time, which can be particularly problematic for complex or highly customized products. Longer lead times not only slow down order fulfillment but also affect customer satisfaction, making effective planning and optimized production processes essential. Another challenge associated with customization is the increased complexity of manufacturing, which requires enhanced coordination and precise planning. Meeting unique customer demands often necessitates specialized raw materials, flexible production processes, and advanced technological solutions, all of which can complicate seamless production. To manage these challenges, companies must implement efficient manufacturing strategies, such as advanced scheduling systems and digital production tools.

Additionally, cost management is a crucial factor, as balancing customization with cost efficiency is essential for maintaining profitability. Excessive customization can drive up material and labor costs and increase manufacturing complexity, which may render the business model unprofitable in the long run. Therefore, companies must develop strategies that align customization with cost efficiency, ensuring sustainable and profitable operations.

2.3 Implementation Strategies

The development of efficient and competitive manufacturing processes requires well-functioning communication, the implementation of advanced planning systems, supplier collaboration, and continuous improvement. Clear and transparent communication channels between sales, production, and customer service play a crucial role in accurately understanding and fulfilling customer demands. Ensuring proper information flow allows all relevant departments to have up-to-date data, minimizing misunderstandings and delays caused by errors. To enhance manufacturing efficiency, the introduction of advanced planning and scheduling systems is essential. These tools enable the optimization of production workflows, the reduction of manufacturing lead times, and the more efficient utilization of resources. Automated planning solutions not only help maximize production capacity utilization but also contribute to faster and more accurate order fulfillment. Close collaboration with suppliers is also fundamental to maintaining uninterrupted production. Ensuring the timely availability of raw materials and components reduces the risk of delays and enhances the stability of production processes. Efficient supplier relationships enable companies to respond more quickly to changing demands and ensure continuous supply. Finally, the principle of continuous improvement plays a key role in increasing efficiency and reducing costs. Regular process reviews and optimization measures allow companies to fine-tune manufacturing operations, eliminate inefficiencies, and integrate innovations. Constant development and the application of modern technologies ensure that the company remains competitive in the long run, even in a rapidly changing market environment. Make-to-order (MTO) represents a customer-centric approach that aligns production with specific demand signals. While it presents challenges, the benefits of increased customer satisfaction, reduced inventory levels, and enhanced market responsiveness make it an attractive strategy for businesses striving for agility in today's competitive markets. As technology continues to advance, the integration of smart manufacturing practices and digital tools further enhances the efficiency of make-to-order strategies.

3 THE BASIC INVENTORY MECHANISMS

The fluctuation of inventory levels at the product level is primarily determined by two key factors: the demand for the specific item and its supply pattern. It is evident that inventory levels are influenced not only by when and how much demand arises for the product, but also by the timing and quantity of replenishment orders placed by the system [9]. The demand pattern is mainly shaped by the company's marketing department, whereas the logistics department is responsible for managing the supply pattern—namely, the inventory control mechanism applied. This mechanism dictates when and how much of a particular stock-keeping unit should be reordered, thereby ensuring the continuous availability of the product in the future [10, 11].

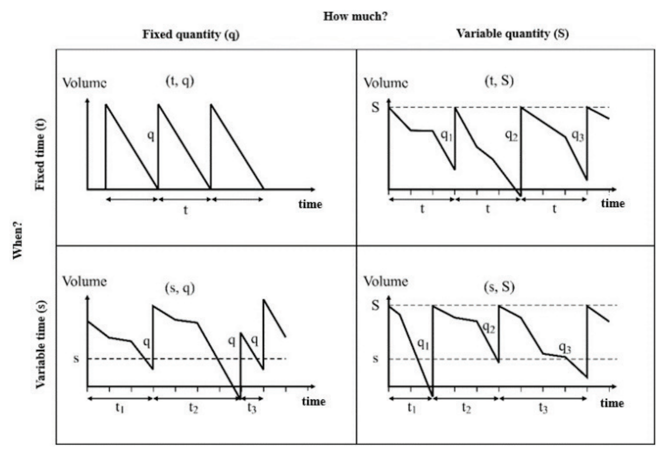

Figure 1 Basic inventory mechanism [12]

Fixed-time-based models (top row) are easier to plan but may not adapt well to demand fluctuations. Variable-time-based models (bottom row) are more flexible and respond to actual needs, potentially leading to more efficient inventory management. Fixed-quantity strategies (left column) provide greater predictability, while variable-quantity strategies (right column) can optimize inventory costs. [13]. Fig. 1 clearly illustrates the differences between inventory strategies and aids in selecting the appropriate method within the supply chain.

4 HYBRID INVENTORY MECHANISM

In the ever-evolving landscape of supply chain management, adopting hybrid inventory control methods has become a strategic necessity for companies aiming to enhance the efficiency of their inventory processes. This chapter explores the concept of hybrid inventory systems by examining their key features, benefits, and practical implementation. Essentially, hybrid mechanisms integrate elements from multiple traditional inventory management models, forming a more flexible and adaptable system. Their goal is to balance the operational efficiency of conventional approaches with the agility of modern, responsive methods.

4.1 General Characteristics

One of the most important characteristics of hybrid inventory mechanisms is flexibility, which allows companies to efficiently adapt to demand fluctuations. By integrating features from both push and pull inventory systems, these mechanisms enable inventory strategies to be simultaneously forward-planning and reactive, ultimately enhancing the overall efficiency and responsiveness of the supply chain. Another key factor is risk reduction, which is achieved through the diversification of inventory management strategies. A company that relies solely on a single inventory management approach is more exposed to market fluctuations and supply disruptions. Hybrid mechanisms enable companies to leverage the advantages of multiple strategies, minimizing the negative effects of stockouts, overproduction, or excessive storage costs.

The main objective of hybrid inventory mechanisms is to enhance inventory management efficiency by adapting strategies to the unique requirements of different product categories or market segments. This method enables companies to balance cost reduction with maintaining high service levels, while continuously improving the overall effectiveness of their inventory operations.

4.2 Benefits of Implementing Hybrid Inventory Mechanisms

The implementation of hybrid inventory mechanisms provides multiple advantages, significantly contributing to a company's efficiency and competitiveness. One of the most notable benefits is the improvement of service levels, as the combination of various inventory management models enables companies to meet customer demands more accurately and quickly. This not only enhances customer satisfaction but also strengthens long-term customer relationships. Cost efficiency is another key advantage of hybrid mechanisms. Adjusting inventory levels according to product features and demand trends can result in substantial cost reductions by minimizing excess storage and handling costs. This is particularly important in industries where inventory-related costs represent a significant proportion of total expenses. Hybrid mechanisms offer significant advantages in risk management by varying inventory strategies, which helps reduce the impact of supply chain disruptions, demand fluctuations, and market uncertainty. By avoiding reliance on a single inventory method, companies can achieve greater stability and resilience in their operations. Flexibility is one of the most critical factors contributing to the effectiveness of hybrid mechanisms. These solutions allow companies to quickly adapt to changing market conditions, enabling them to maintain their competitive advantage and effectively respond to fluctuations in demand or supplier conditions.

In corporate operations, two fundamental and relatively simple inventory control systems — or their combination — have become widely adopted [9]:

- Continuous review system: in this approach, inventory levels are monitored on an ongoing basis, allowing decisions to be made at any time based on current stock status and demand. The two main decision parameters are the order quantity (q) and the reorder point (s), which represents the inventory level that triggers a replenishment order for a fixed quantity. This model is commonly referred to as the (s, q) inventory system.
- Periodic review system: this method involves checking inventory levels at regular, predefined intervals — such as weekly or monthly. The order quantity is determined based on the stock level recorded at the time of review. Here, the quantity to be ordered is calculated as the difference between the target maximum inventory level (S) and the actual available inventory (I_a) at the review point. This type of system is known as the (t, S) inventory model.

5 DESCRIPTION OF HYBRID INVENTORY MECHANISMS IN MAKE-TO-ORDER (MTO) MANUFACTURING SYSTEMS

The use of hybrid inventory strategies in Make-to-Order (MTO) production brings various advantages, including decreased inventory levels, more efficient production workflows, and higher levels of customer satisfaction. However, implementing and maintaining such a system can present significant challenges, particularly in aligning manufacturing and logistics processes. We only deal with three hybrid variants, as the combination of (t, q) and (t, S) (combined fixed order system) is not suitable for MTO systems. This is because Make-to-Order (MTO) production is characterized by manufacturing products only after receiving customer orders, which leads to highly variable demand. As a result, MTO systems generally require more flexible, event-driven hybrid inventory management models.

5.1 Combination of (*t*, *q*) and (*s*, *S*) – Adaptive Periodic System

Its operation is characterized by conducting inventory checks at predetermined intervals (t), but if the current stock level drops below a predefined threshold (s), an immediate order is triggered, even before the scheduled replenishment time. The advantage of this system is that it balances scheduled inventory replenishment and demand-driven ordering. The system's efficiency is particularly beneficial in a Make-to-Order (MTO) manufacturing environment, where production is solely based on incoming orders. The adaptive inventory management mechanism ensures continuous monitoring of raw material and component stocks while allowing replenishment to occur in a timely and flexible manner. This minimizes excess inventory costs and reduces production delays caused by stock shortages.

By combining scheduled and immediate ordering strategies, this system enables companies to respond effectively to fluctuating demand while maintaining supply chain stability and production continuity.

Let $I_{(t)}$ represent the inventory level as a function of time. Inventory depletion occurs based on the demand function $D_{(t)}$:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \quad (1)$$

where $O_{(t)}$ follows two replenishment rules.

Replenishment follows two conditions:

- *Scheduled replenishment:*

$$O_{(t)} = q, \text{ if } t = nT, n \in \mathbb{N}, \quad (2)$$

meaning that a fixed quantity q is ordered at the end of every T interval.

- *Immediate replenishment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } I_{(t)} \le s, \quad (3)$$

meaning that if the inventory level drops below s, an immediate order is triggered to restore stock up to S.

This inventory model offers multiple advantages for MTO-based manufacturing:

- Balancing fixed-interval and demand-driven replenishment: The combination of time-based (t, q) and event-driven (s, S) policies ensures continuous inventory availability.
- Minimized inventory holding costs: The system replenishes stock only when necessary, reducing storage and carrying costs.
- Quick response to demand fluctuations: In MTO production, demand variability can be managed effectively through dynamic ordering strategies.

This hybrid inventory management system ensures supply chain stability, while minimizing excess stock and reducing production delays caused by material shortages.

5.2 Combination of (*s*, *q*) and (*s*, *S*) – Flexible Minimum Order System

This system generates a fixed quantity order (q) when the inventory level reaches the threshold (s), but if demand is higher than average, the order quantity can be increased up to the maximum stock level (S). Its advantage lies in its ability to flexibly handle demand fluctuations, ensuring continuous supply while minimizing stockouts. In a Make-to-Order (MTO) manufacturing environment, ensuring the availability of raw materials while minimizing storage costs is crucial. In this model, when inventory reaches the threshold (s), a fixed order (q) is triggered, but if demand forecasts indicate increased demand, the order quantity can be adjusted up to the maximum stock level (S). This system ensures continuous raw material availability, responds flexibly to demand changes, and minimizes inventory holding costs, as additional stock is procured only when necessary, contributing to efficient inventory management and cost optimization. Again, let $I_{(t)}$ represent the inventory level at time (t). The inventory level follows the equation:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \quad (4)$$

where $D_{(t)}$ represents demand at time (t), and $O_{(t)}$ follows two replenishment rules.

Replenishment follows two conditions:

- *Fixed minimum order:*

$$O_{(t)} = q, \text{ if } I_{(t)} \le s, \quad (5)$$

when inventory falls below s, a fixed quantity q is ordered.

- *Dynamic order adjustment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } I_{(t)} \le s \text{ and } \hat{D}_{(t)} > \mu, \quad (6)$$

if inventory falls below s and the forecasted demand $\hat{D}_{(t)}$ exceeds the average demand μ\muμ, the system replenishes stock up to the maximum level S.

This inventory model offers multiple advantages for MTO-based manufacturing:

- The system guarantees that raw materials are available when production begins, preventing disruptions.
- By dynamically adjusting order quantities, it minimizes stockouts and ensures production continuity.
- Stock replenishment occurs only when necessary, reducing excess inventory and storage costs.

This hybrid inventory control model optimally balances supply stability and cost efficiency, making it an effective solution for MTO-based production environments.

5.3 Combination of (*t*, *S*) and (*s*, *q*) – Hybrid Time-Based and Event-Driven Model

This model places orders at regular intervals (t) to replenish inventory up to the maximum stock level (S). However, if the inventory level drops below a critical threshold (s) before the scheduled replenishment, an emergency order is triggered, replenishing stock with a fixed quantity (q). The key advantage of this system is that it effectively integrates both time-driven and demand-driven inventory management, creating an optimal balance between scheduled and immediate replenishments. In a Make-to-Order (MTO) production environment, this model is particularly effective. Certain raw materials are ordered at fixed intervals (t) to maintain continuous supply, ensuring that production has the necessary inputs. However, if the stock level of a material drops below the predefined threshold (s) before the scheduled replenishment, an emergency order is placed to restock a fixed quantity (q), preventing potential disruptions in the production process. This system provides several benefits for MTO production. Scheduled orders help reduce the risk of stockouts while simultaneously lowering ordering costs. Additionally, the event-driven ordering mechanism ensures that production does not come to a halt due to sudden increases in demand, maintaining operational continuity. Moreover, this hybrid approach enhances inventory planning within the supply chain, supporting more efficient resource allocation and sustainable inventory management. Again, let $I_{(t)}$ represent the inventory level at time (t). The inventory level follows the equation:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \tag{7}$$

where $D_{(t)}$ represents demand at time (t), and $O_{(t)}$ follows two replenishment rules.

Replenishment occurs in two ways:

- *Time-based replenishment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } t = nT, n \in \mathbb{N}. \tag{8}$$

This means that at the end of every T interval, inventory is replenished up to the maximum level (S), regardless of demand fluctuations.

- *Event-driven emergency order:*

$$O_{(t)} = q, \text{ if } I_{(t)} \le s, \tag{9}$$

If inventory drops below the critical threshold (s) before the next scheduled replenishment, an immediate order is triggered to restock a fixed quantity (q). This inventory model offers multiple benefits for MTO production environments. The time-based replenishment mechanism reduces the risk of stockouts while keeping ordering costs lower due to scheduled orders. Meanwhile, the event-driven ordering strategy ensures that production does not halt in the event of sudden demand surges, maintaining operational continuity. Additionally, this hybrid approach enhances inventory planning within the supply chain, enabling more efficient resource allocation and sustainable inventory management. Time-based ordering strategies ensure continuous material availability, while event-driven restocking helps manage demand fluctuations more effectively. Overall, the combination of (t, S) and (s, q) creates a balance between scheduled and emergency replenishments, ensuring smooth manufacturing processes and optimized inventory management in MTO-based production environments.

5.4 Mathematical Model on Hybrid Inventory Strategy in MTO Environments

In a Make-to-Order (MTO) production environment, inventory management aims to minimize shortages of raw materials and components. This adaptive inventory mechanism adjusts dynamically to demand fluctuations:

- *The demand function $D_{(t)}$ may be deterministic or stochastic:*

$$D_{(t)} \sim N(\mu, \sigma^2) \text{ (assuming normally distributed demand)} \tag{10}$$

- *The optimal minimum inventory level s^* and maximum inventory level S^* can be estimated as follows:*

$$s^* = \mu L + z\sigma\sqrt{L}, \tag{11}$$

$$S^* = s^* + q. \tag{12}$$

Where $D_{(t)}$ demand as a function of time: represents the demand at a specific time (t), L the lead time, z the standard normal distribution value corresponding to the desired service level, $N(\mu, \sigma^2)$ assumes that demand follows a normal distribution, defined by two parameters: μ expected demand (the long-term average demand level observed over time), σ demand standard deviation (indicates how much demand may fluctuate around the average value. A higher standard deviation implies greater variability in demand), σ^2 demand variance (the square of the standard deviation, measuring the extent of demand fluctuations).

5.5 Practical Example of Hybrid Inventory Mechanism in an MTO Environment

To demonstrate the practical applicability of the proposed hybrid inventory mechanism, this section presents a real-life inspired (fictional) example based on an MTO production environment. A manufacturing company operating under an MTO production strategy produces customized electronic components. The company's raw material, a special type of microchip, is procured from an external supplier. The following data are available:

- Average weekly demand (μ) = 200 units
- Standard deviation of demand (σ) = 50 units
- Lead time (L) = 2 weeks
- Desired service level = 95% → z = 1.65
- Fixed order quantity (q) = 300 units
- Maximum stock level (S) = calculated
- Review period (T) = 2 weeks
- Safety stock threshold (s) = calculated.

According to the hybrid inventory model described earlier, the optimal minimum and maximum inventory levels are calculated as:

$$s^* = \mu L + z\sigma\sqrt{L} \tag{13}$$

$$S^* = s^* + q \tag{14}$$

$$s^* = 200 \cdot 2 + 1.65 \cdot 50 \cdot \sqrt{2} = 400 + 116{,}7 \approx 517 \text{ units} \tag{15}$$

$$S^* = 517 + 300 = 817 \text{ units} \tag{16}$$

From an operational perspective, it can be concluded that the company is required to apply a hybrid inventory mechanism. The example illustrates a hybrid inventory strategy that combines both time-based and event-driven mechanisms. In this system, the company reviews its inventory levels every two weeks. If the inventory remains above the safety threshold of 517 units during this period, no action is taken. However, if the inventory level drops below 517 units at any time within the review period, an emergency replenishment order is triggered to restore the stock level up to 817 units, ensuring continuity in production. Regardless of emergency replenishments, a fixed order of 300 units is also placed at the end of every two-week review period, following a regular ordering rhythm. This combination of scheduled and demand-responsive ordering enhances both supply chain stability and responsiveness in a Make-to-Order (MTO) production environment.

6 CONCLUSION

The digitalization of industrial production and the expansion of the Industry 4.0 era have radically transformed supply chain and inventory management strategies. Through intelligent systems, data analytics, and automation, companies can optimize their processes, reduce excess inventory, and respond more quickly to market changes. This study provides a detailed analysis of how traditional push and pull strategies are integrated into a hybrid inventory mechanism, which is particularly beneficial in Make-to-Order (MTO) manufacturing systems, where production is initiated solely based on incoming orders. The objective of this innovative approach is to achieve greater flexibility, cost efficiency, and sustainability, while simultaneously enhancing customer satisfaction and strengthening market competitiveness. The study examines various inventory management mechanisms and then presents their combinations in the form of different hybrid systems. These models enable the simultaneous application of scheduled and demand-driven ordering mechanisms, optimizing inventory levels, minimizing storage costs, and reducing the risk of production disruptions and delays caused by stockouts. Furthermore, mathematical models are used to determine optimal reorder points and inventory levels, allowing companies to effectively manage demand fluctuations and ensure a stable supply of raw materials necessary for uninterrupted production.

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7 REFERENCES

[1] Zhang, X., Sheng, G., Chen, L., Lu, X., Ming, X., & Qiu, S. (2024). Hybrid order priority confirmation and production batch optimization for mass personalization flexible manufacturing (MPFM) model. *Advanced Engineering Informatics, 62*, 102739. https://doi.org/10.1016/j.aei.2024.102739

[2] Efthymiou, O., & Ponis, S. T. (2024, May). Decision Making in the Intelligent Distribution Centers of the Industry 4.0 Era: A Structural Approach. In *Olympus International Conference on Supply Chains* (pp. 228-247). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-69344-1_17

[3] Beemsterboer, B., Land, M., & Teunter, R. (2016). Hybrid MTO-MTS production planning: An explorative study. *European Journal of Operational Research, 248*(2), 453-461. https://doi.org/10.1016/j.ejor.2015.07.037

[4] Claudio, D., Zhang, J., & Zhang, Y. (2010). A simulation study for a hybrid inventory control strategy with advance demand information. *International Journal of Industrial and Systems Engineering, 5*(1), 1-19. https://doi.org/10.1504/IJISE.2010.029754

[5] Jia, Y., Weng, W., & Fujimura, S. (2017, May). A hybrid MTS-MTO production model with a dynamic decoupling point for flexible flow shops. In *IEEE/ACIS 16th International Conference on Computer and Information Science (ICIS2017)*, 803-807. https://doi.org/10.1109/ICIS.2017.7960102

[6] Kim, E., & Min, D. (2021). A two-stage hybrid manufacturing model with controllable make-to-order production rates. *Journal of Manufacturing Systems, 60*, 676-691. https://doi.org/10.1016/j.jmsy.2021.07.014

[7] Zhang, Z. G., Kim, I., Springer, M., Cai, G. G., & Yu, Y. (2013). Dynamic pooling of make-to-stock and make-to-order operations. *International Journal of Production Economics, 144*(1), 44-56. https://doi.org/10.1016/j.ijpe.2013.01.012

[8] Svoronos, A., & Zipkin, P. (1988). Estimating the performance of multi-level inventory systems. *Operations research, 36*(1), 57-72. https://doi.org/10.1287/opre.36.1.57

[9] Gelei, A. (1976). *Logisztikai döntése – fókuszban a disztribúció*. Akadémiami Kiadó Hungary. ISBN 978630593809 (in Hungarian)

[10] Chikán, A., & Nagy, M. (1978). *Készletgazdálkodás*. Tankönyvkiadó, Budapest, Hungary. ISBN: 9632212258 (in Hungarian)

[11] Demeter, K. (2008). *Készletek a folyamatokban*. In: Demeter, K., Gelei, A., Jenei, I., & Nagy, J. (eds.) *Tevékenységmenedzsment*. Aula Kiadó, Budapest, Hungary, 173-194. ISBN: 9789639698413 (in Hungarian)

[12] Chikán, A. (1983). *Készletezési modellek*. Közgazdasági és Jogi Könyvkiadó, Budapest, Hungary. ISBN: 9632212258 (in Hungarian)

[13] Lau, A. H. L., Lau, H. S., & Zhou, Y. W. (2007). A stochastic and asymmetric-information framework for a dominant-manufacturer supply chain. *European Journal of Operational Research, 176*(1), 295-316. https://doi.org/10.1016/j.ejor.2005.06.054

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Visualization of Social Life Cycle Assessment and Ethics Audit Outcomes in the Context of a Circular Manufacturing Ecosystem

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Abstract: The identification and consideration of social and ethical aspects are key enablers to achieving sustainable production, including human-centrism. Existing social life cycle assessment and ethical audit methods identify relevant risks and their impacts on such complex systems. In the context of a business ecosystem, an integrated view of the assessments' outcomes is missing. Addressing this gap, we propose an extension of the V² value network notation. By combining economic and social sustainability aspects, the resulting holistic view creates a comprehensive visualization of the overall system. This view serves as the basis for the analysis and communication of complex socio-technical systems' aspects. The proposed extension of the notation is presented, and its application is demonstrated by means of a case study of a platform-based circular manufacturing ecosystem that enables the reuse of assembly lines.

Keywords: circular economy; ethical audit; social life cycle assessment; sustainable production; value network

1 INTRODUCTION

Ideally, a successful circular economy contributes to all three dimensions of sustainable development (economic, environmental and social) [1]. In practice and in particular, the social dimension is not always adequately considered, which impedes the uptake of circular strategies [1]. The social dimension lacks research, particularly concerning circularity in the manufacturing industry [2]. To ensure the oftentimes missing social pillar is properly embedded within circular economy strategies, social indicators need to be assessed to identify the positive and negative impacts that arise from the implementation of a circular economy model [3].

In addition, when new technologies are introduced, there is always a risk of unethical consequences. Especially nowadays, since legal compliance is not always keeping pace with digital developments, we require approaches that ensure ethical digital innovations [4].

Existing social and ethical assessment methods [5, 6] identify relevant risks and their impacts on such complex ecosystems. Value network models [7-11] provide a means of abstraction, visualization and analysis for business ecosystems such as the circular manufacturing ecosystem. However, an integrated view of the above-mentioned assessments' outcomes in value network models is missing. To address this gap, we propose an extension of the V² value network notation [7, 12-14] in order to combine economic and social sustainability aspects, thus resulting in a holistic view that creates a comprehensive visualization of the overall system. This extension serves as the basis for analysis and communication of the aspects of complex socio-technical systems, such as the Circular Manufacturing Ecosystem (CME) in the research project Assembly Lines in Circulation (ALICIA) [15], in order to better understand the relation of social and ethical risks to economic aspects. The application of the V² value network extension is demonstrated in the case of the ALICIA CME.

To foster sustainable production, ALICIA [15] aims to develop a CME platform. This platform will be a one-stop shop for second-hand equipment, enabling faster and easier selection, procurement, delivery, installation and commissioning of second-hand equipment while also decreasing factory owners' costs, as purchasing second-hand equipment is cheaper than purchasing new build equipment. Besides production performance, quality and economical aspects, social aspects, such as existing worker skills and environmental aspects, are also considered. In addition, the platform ecosystem will be open to various service providers, offering complementary services that are required for covering the entire life cycle of equipment. In order to enable all this, various digital services will be developed in the course of the ALICIA project. Their detailed functionalities, interrelation as well the additional services that must be offered via the platform have yet to be defined.

The remainder of this paper is structured as follows: Section 2 describes the social and ethical assessment methods applied in the ALICIA project. Section 3 describes our extension of the V² value network notation. Its application in a case study in the ALICIA project is demonstrated in section 4. The single case study method is based on [16]. Section 5 concludes the paper, discussing the results, contributions to research and practice, limitations and future research.

2 SOCIAL AND ETHICAL ASSESSMENT

This section describes the selected methods for the social and ethical assessment and how they were applied in the context of the ALICIA research project, including the elements that were used to describe the outcomes of the assessment.

2.1 Social Assessment

The ALICIA CME encompasses a diverse array of digital tools. A significant portion of these tools is deployed prior to the integration of second-hand equipment into customers' assembly lines. Most of these tools contain, apart from their technical processes, non-technical processes that affect the stakeholders (e.g., factory owners, workers, or other value chain actors) of ALICIA. To guarantee the socially responsible implementation of all tools and processes across the spectrum of ALICIA's stakeholders, it is imperative to assess their social impacts, along with the associated social risks.

ALICIA utilizes various digital and AI-based tools that potential users might view as risky or unsafe. As a result, they may show a lack of willingness to apply such technological innovations. This could pose barriers to the widespread implementation of ALICIA when compared to traditional second-hand marketplaces. To address both the social risks that the ALICIA platform may bring and the barriers users may have concerning the use of the platform, a Social Life Cycle Assessment (S-LCA) has been conducted.

S-LCA is becoming an increasingly important method for ensuring holistic sustainability assessments. It allows for the assessment of the social impacts of products, services, or organizations across their life cycles [5]. Potential social impacts are defined by the United Nations Environment Programme (UNEP) as "the likely presence of a social impact, resulting from the activities/behaviours of organizations linked to the life cycle of the product or service and from the use of the product itself" [5]. S-LCA is an iterative methodology, which means that the assessments' outcomes can be improved over time, going through several assessment loops and moving from more generic/potential results to more site- and case-specific ones.

A leading framework for conducting S-LCA has been developed by UNEP (latest version published in 2020) [5] and is in large part based on the ISO 14040 framework for Environmental LCA (E-LCA) [5, 17]. Still, S-LCA allows, which is different from the E-LCA, the quantification of social impact indicators which are largely not simple to determine [18] for complementing the results of E-LCA.

The S-LCA methodology by UNEP is considered a keystone of S-LCA approaches [19] due to numerous applications within case studies and research. Another existing approach is the ISO/DIS 14075 - Environmental management - principles and framework for social life cycle assessment [20]. However, at the beginning of the ALICIA project, the UNEP framework was in a more mature state than the ISO/DIS 14075. There is a very limited amount of research available regarding social impacts of CE in manufacturing and thus few opportunities for validating the results obtained with a new method. Therefore, the UNEP S-LCA framework [16] was chosen as a base method for analysing the social impacts of ALICIA.

The applied methodology comprises four main phases: 1) goal and scope definition, 2) social life cycle inventory analysis, 3) social life cycle impact assessment (impact pathway based on [21]) and 4) interpretation of the results.

The following descriptive elements (see also Tab. 1) are used to summarize the outcomes of the applied S-LCA approach according to [5]: The **life cycle stage** represents the life cycle of the product as defined in ISO 14040 [17] and 14044 [22]. The **stakeholder category,** according to the UNEP S-LCA guidelines, includes six total stakeholder categories (workers, local communities, value chain actors, consumers, children and society) to consider when performing an S-LCA. Stakeholder categories, which are the basis of every S-LCA, have to be linked to **impact categories** that represent socially meaningful attributes or themes. **Inventory indicators** are specific definitions derived from the collected data during the social life cycle inventory analysis and relate directly to each life cycle. Every inventory indicator belongs to a stakeholder and impact category. It is considered as the beginning of a cause-effect chain and thus the cause of midpoint and endpoint impacts. **Midpoint indicators** represent impacts on the middle of the cause-effect chain. **Endpoint indicators** refer to impacts that occur as a consequence, at the end of the chain. To define those indicators, social mechanisms and collected inventory indicators are required to assess these midpoint and endpoint indicators [5]. **Potential solutions** (or mitigation strategies) describe how this (negative) impact might be avoided.

2.2 Ethical Assessment

When new technologies are introduced, there is always a risk that this may unintentionally lead to unethical consequences and therefore requires approaches that ensure ethical digital innovations [4].

It is necessary to analyse which ethical issues the technology may cause and to assess potential impacts and to ensure the ethical implementation of the new technology. Doing this facilitates the design of the technological innovations in a more ethical and value-sensitive way [23]. Within the context of CE, digital technologies can enable services that are beneficial for CE implementation, such as the provision of technical support, evaluating a product's life cycle and maintaining or enhancing a product [24].

The digital technologies, which are developed in ALICIA, were the subject of analysis of the ethical assessment. The chosen approach for this ethical assessment was a digital ethics audit. The methodology from this auditing framework contains components of ISO 19011 (guidelines for auditing management systems) [25], ISO 31000 (risk management guidelines) [26] as well as literature and other sources from existing auditing approaches, including ethical auditing and other auditing fields (e.g., ESG auditing [6]). ISO 19011 especially represents a critical part of this auditing process and includes, among other aspects, a risk-based approach to the principles of auditing.

The aim of this audit was to identify and mitigate the risks of ALICIA's technologies, designing appropriate mitigation measures as feedback into the project design process, so that later, all affected stakeholders feel safe using those technologies [27].

The entire auditing process contains five auditing cycles, and every auditing cycle contains several sub-cycles that split the cycle's task into its actions or methods. The process was conducted with help of desk research, interviews and workshops.

- Cycle 1 - Scope setting: 1.1 audit objectives, 1.2 identifying stakeholders, and 1.3 establishing values and identifying risks
- Cycle 2 - Risk analysis: 2.1 aggregating risks, 2.2 risk prioritization
- Cycle 3 - Validation: 3.1 internal validation, 3.2 validation with involved partners
- Cycle 4 – Mitigation: 4.1 communicating design considerations, 4.2 designing of mitigations by all partners

- Cycle 5 - Evaluation and report: 5.1 finalizing audit report, 5.2 presenting audit results to all partners.

Within the project so far, Cycle 1 and Cycle 2 have been conducted. The following descriptive elements (see also Tab. 1) were used to summarize the outcomes of the applied ethical assessment approach: **technology** refers to the objects to be audited. In ALICIA, these are the digital tools of the platform and the **stakeholders** who are affected by the technology. When auditing the ethics of digital technologies, it is imperative to define and incorporate **values**, as defined by [28, 29], into the technology. These values help to shape the extent to which future users can utilize and potentially be influenced by the technology [30]. **Risk (affected stakeholders)**: Since values are always linked to certain risks (for each value, multiple risks can exist), it can often be challenging to define values without also considering the associated risks. Therefore, Cycle 1 also aims to identify preliminary potential risks related to those values and those that affect certain stakeholders. Cycle 2 deals with the risk analysis. It aims to identify further risks and to subsequently analyse the priority of all existing risks. To do so, the "risk prioritization" sub-cycle assesses each risk, based on [31], by its likelihood of occurrence (**risk likelihood**) and severity levels (**risk impact**). The remaining steps are validating the identified impacts and to start mitigating the negative impacts they may bring, which is described as **mitigation** in the outcome of the assessment. Finally, the outcomes are evaluated and reported.

3 EXTENSION OF THE V² VALUE NETWORK NOTATION

The V^2 value network notation [12] used in the presented work builds on the notation of Biem and Caswell [7], which synthesizes and extends concepts of e3 e-business modelling [6], the c3-value method [9] and Allee's [10, 11] concept of intangibles [5]. The V^2 notation is structured around dedicated layers which serve to visualize and analyse actors, their value exchanges, motivations, legal aspects and needs (see Fig. 1). These layers have been developed over the course of various research projects over the past decade [12, 13]. In the recent literature, value network models are still investigated in the context of business modelling [14]. As stated by [32], visualizations improve communication, support collaboration and foster human engagement by supporting cognitive processes and augmenting the capacity of the human mind and creating a common understanding.

In order to integrate the outcomes of a social and ethical assessment into a value network model, we, the authors, developed an extension of the V^2 value network notation. By combining economic and social sustainability aspects, the resulting holistic view creates a comprehensive visualization of the overall system. This view should serve as the basis for the analysis and communication of complex socio-technical systems' aspects.

In order to define a means of visualizing the outcomes of S-LCAs and ethics audits, we compared and consolidated their elements with elements used in the application of risk management to medical devices [33], which represents a state-of-the-art risk management standard (see Tab. 1). Based on that we defined the risk layer extension of the V^2 notation (see Tab. 2 and Fig. 2).

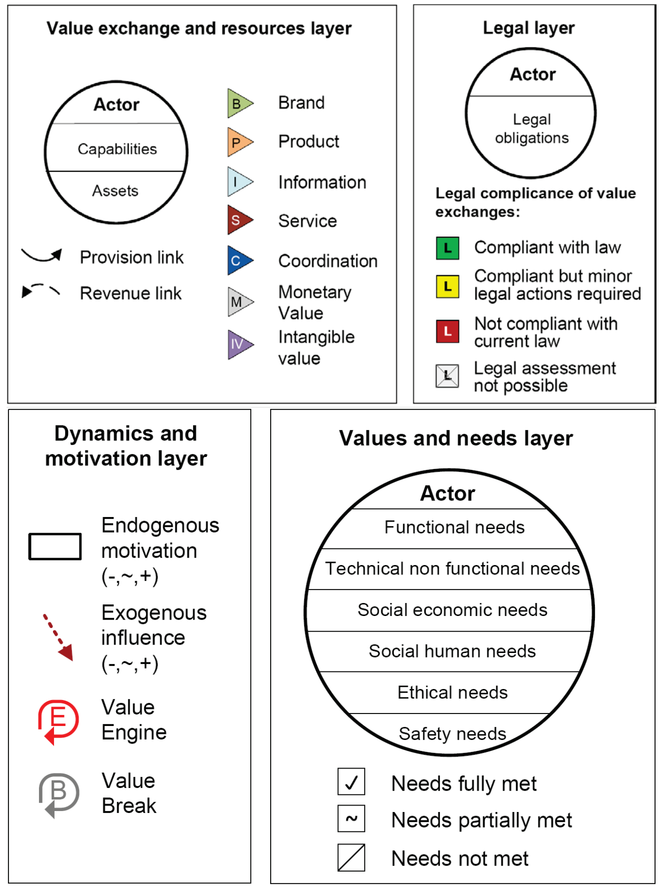

Figure 1 The analysis layers of the V² value network notation (figure from [12] based on [7, 13, 14])

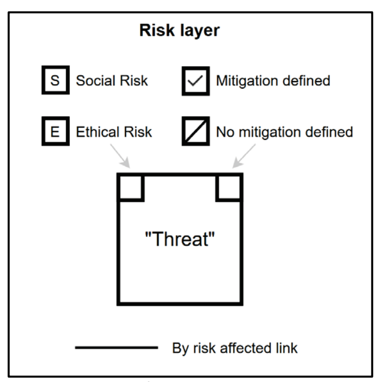

Figure 2 Representation of risks in the V² value network notation

The elements consolidated to a common risk layer, indicated by a merged column in Tab. 2, are described in the following. The elements "**impact category**" and "**value**" are represented by the element "**value category**", which describes either the social or ethical values the risk relates to. "**Inventory indicator**" and "**risk (affected stakeholders)**" are represented by the element "**threat**" of the risk layer. The newly added element "**description**" allows a further elaboration of the identified threat. The element "**source of information**" was also added to assist with keeping track of where the information about the threat was identified from e.g. data sources or references. "**Mitigation**" is used to commonly describe any potential solution for social as well as ethical risks. The "**stakeholder categories**" represent the affected stakeholders for both assessments. The remaining elements were considered as too specific for this type of assessment when defining a common element. Therefore, these elements were taken over to the new risk layer without modifications. The common grounding was finally validated with the social and ethical assessment expert from the ALICIA project.

Table 1 Comparison of elements of S-LCA, the ethical audit and risk analysis

S-LCA elements (based on UNEP [5])	Ethics audit elements (based on ISO-19011 [25] and ISO-31000 [26])	Risk analysis elements (based on ISO-14971 [33])
Life cycle	Technology	Life cycle stage
Impact category	Value	Category of hazard
-	-	Hazardous situation
Inventory indicator	Risk (affected stakeholders)	Event
Midpoint impact	-	Harm
Endpoint impact	-	
-	Risk likelihood	Probability of occurrence
-	Risk impact	Severity of impact
Potential solution	Mitigation	Mitigation
Stakeholder category	(already included in "Risk")	Groups of people affected by the harm

Table 2 Consolidated risk layer definition for the V^2 value network notation based on [5, 25, 26, 33]

Social risk elements	Ethical risk elements	Description of element
Life cycle stage	Technology	In which situation (activity, technology) the threat can occur
Value category		Defined categories that either describe social or ethical values.
Threat		The possible negative (harmful) event.
Description		Additional description clarifying the threat.
Source of information		Describes from which source the threat was identified.
Midpoint impact	-	Midpoint indicators represent impacts in the middle of the cause-effect chain.
Endpoint impact	-	Endpoint indicators refer to impacts that occur as a consequence, at the end of the chain.
-	Probability of occurrence	Probability of occurrence is a quantitative ranking defined by the assessor.
-	Severity of impact	Severity of impact is a quantitative ranking defined by the assessor.
Mitigation		This is a possible solution so that the threat does not occur
Stakeholder categories		Describes affected stakeholders and is used to identify affected actors in the value network.

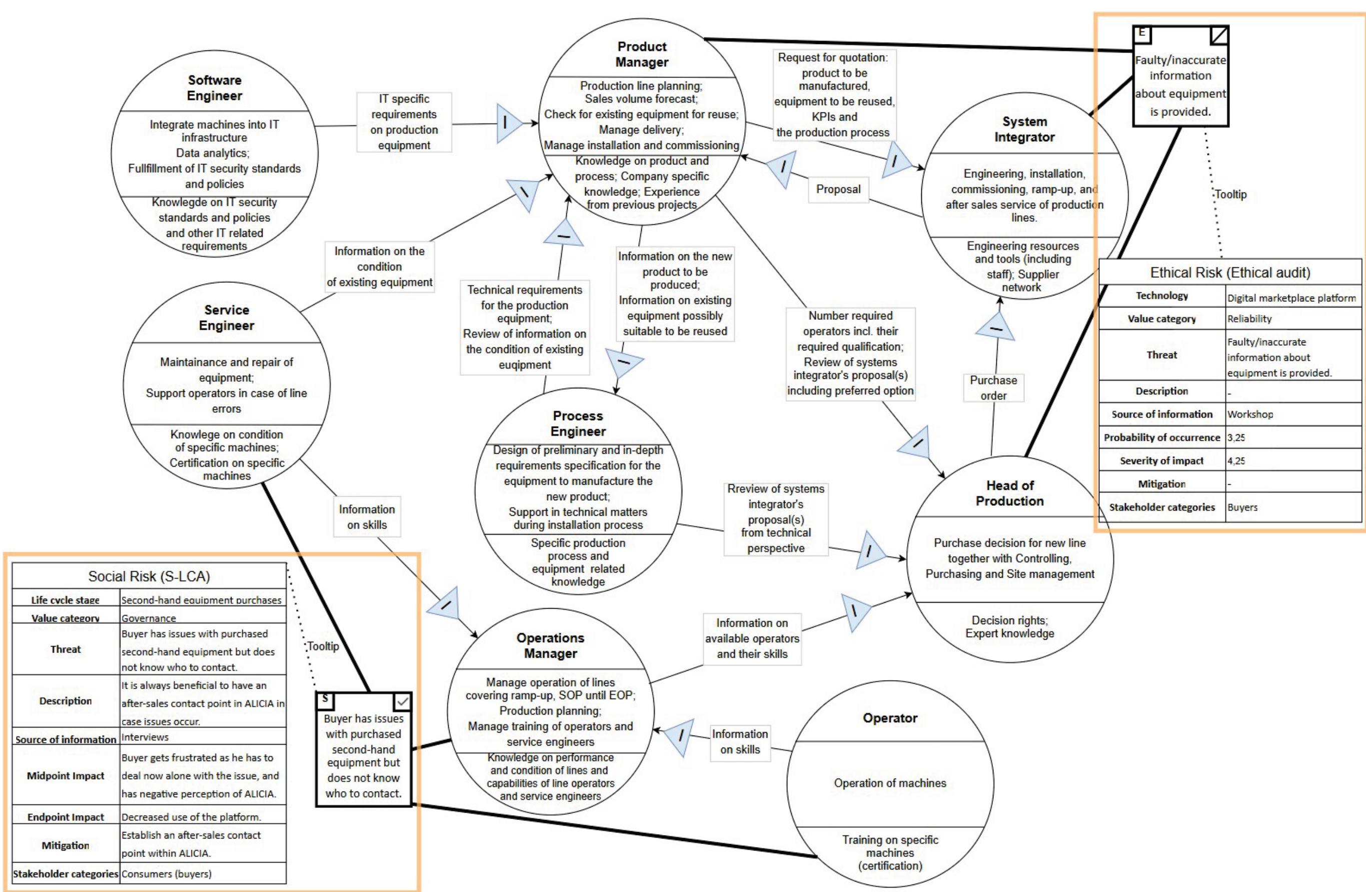

Figure 3 Example of visualizing social and ethical risks in a value network

To extend the existing V^2 value network notation, we defined the following symbols (see Fig. 2) to represent a risk in a value network. Each identified risk is represented by a square. Each square shows the information that has been documented as a "threat" in the assessment. The small upper left square indicates whether the risk was identified from the social (S) or the ethical (E) assessment. The small square in the upper right corner indicates if a mitigation has already been defined for the risk. This shall provide a quick overview in the overall value network, in which risks still need to be handled in terms of identification and documentation of an appropriate mitigation. With the help of a "tooltip" function, which is planned to be implemented in the EcoViz tool [34], the detailed information about the risk, as defined in Tab. 2, is displayed. This function is also illustrated in Fig. 3.

4 DEMONSTRATION OF THE RISK LAYER

In this section, we demonstrate the application of the V2 value network notation, including the risk layer with the case of ALICIA. The value network analysis, shown in Fig. 3, was conducted in the context of requirements engineering of the ALCIA CME platform. It includes typical actors at a factory owner, including their capabilities and assets, and shows the exchanges of information in a scenario in which a line for the assembly of a new product is bought. In addition to the value exchange and resources layer, which supports the visualization of economic value exchanges, the newly developed risk layer has been applied to visualize one social and one ethical risk, which were identified in the social and ethical assessment in the ALICIA project. Their visualizations are highlighted with an orange square in Fig. 3. Both risks describe "Buyers" as their stakeholder category. It is clearly shown in the context of this scenario that the two risks may affect very distinct types of actors at a factory owner. The "tooltip" function reveals all details documented as defined in Tab. 2 for each identified risk. With this risk layer it is now possible to additionally visualize results from a social and ethical assessment in the economic context of a value network. This enables an integrated view on the economic and social sustainability dimension of a complex system.

5 CONCLUSIONS

Our work provides further insights on how social and ethical assessments can be conducted in the context of a circular economy and how to visualize the assessment's outcome in a networked economic context. By combining economic and social sustainability aspects, the resulting holistic view creates a comprehensive visualization of the overall system. This view can serve as the basis for the analysis and communication of complex socio-technical systems, such as the ALICA circular manufacturing ecosystem.

The value network analysis with the risk layer sets the risk in a specific context and relates it to specific actors rather than purely generic stakeholder categories. Further insights on impact, beyond the specific actor, may be gained through this because of the visualization of relations between the actors in the system. Furthermore, the visualization in the value network may also support certain steps of the assessment itself, such as the validation cycle of the ethical audit.

Nevertheless, a validation of the visualization and its benefits is still required. So far, it has only been demonstrated in a single case. Additional applications in further cases are required. As a next step, we will also focus on the integration of the new risk layer in the existing EcoViz tool [34] to support practical applicability and foster validation. Additional features may be required to tackle the challenge of visualizing a large number of risks to prevent visual overload. These features may include the possibility to aggregate risks and to deep dive into specific groups of actors. Furthermore, we also plan to extend the notation by also integrating the visualization of environmental impacts in the value network and to include a comparison of other existing risk analysis frameworks in this context.

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6 REFERENCES

[1] Bianchini, A., Guarnieri, P. & Rossi, J. (2022). A Framework to Assess Social Indicators in a Circular Economy Perspective. *Sustainability*, *14*(3), 7970. https://doi.org/10.3390/su14137970
[2] García-Muiña, F., et al. (2021) Industry 4.0-Based Dynamic Social Organizational Life Cycle Assessment to Target the Social Circular Economy in Manufacturing. *Journal of Cleaner Production*, *327*, 129439. https://doi.org/10.1016/j.jclepro.2021.129439
[3] Padilla-Rivera, A., et al. (2021). Social Circular Economy Indicators: Selection through Fuzzy Delphi Method. *Sustainable Production and Consumption*, *26*, 101–110. https://doi.org/10.1016/j.spc.2020.09.015
[4] Sopra Steria. (2020). *Digital Ethics: breaking down complexity to enable practical action*. Whitepaper.
[5] United Nations Environment Programme. (2020). *Guidelines for Social Life Cycle Assessment of Products and Organisations 2020*. https://wedocs.unep.org/20.500.11822/34554
[6] Emerick, D. (2025, March 7). What is an ESG Audit? Retrieved from https://esgthereport.com/what-is-esg/the-g-in-esg/what-is-an-esg-audit/
[7] Biem, A. & Caswell, N. (2008). A value network model for strategic analysis. *Proceedings of the 41st Annual Hawaii International Conference on System Sciences (HICSS 2008)*, Waikoloa, HI, USA, 361-367. https://doi.org/10.1109/HICSS.2008.43

[8] Gordijn, J., Akkermans H. & van Vliet H. (2000). Business Modelling Is Not Process Modelling. *Conceptual Modeling for E-Business and the Web*. Springer Berlin Heidelberg, 40–51. https://doi.org/10.1007/3-540-45394-6_5

[9] Weigand, H., et al. (2007) Strategic analysis using value modelling–The c3 approach. *Proceedings of the 40th Hawaii International Conference on System Sciences (HICSS'07)*, Waikoloa, HI, USA. https://doi.org/10.1109/HICSS.2007.501

[10] Allee, V. (2003). *The future of knowledge: Increasing prosperity through value networks.* Butterworth - Heinemann.

[11] Allee, V. (2009). Value-creating networks: organizational issues and challenges. *The Learning Organization, 16*(6), 427. https://doi.org/10.1108/09696470910993918

[12] Vorraber, W. & Müller, M. (2019). A networked analysis and engineering framework for new business models. *Sustainability*, 11(21), article 6018. https://doi.org/10.3390/su11216018

[13] Vorraber, W. & Vössner, S. (2011). Modeling endogenous motivation and exogenous influences in value networks of information service systems. *Journal of Convergence Information Technology, 6*(8), 356-363. https://doi.org/10.4156/jcit.vol6.issue8.43

[14] Szopinski, D., et al. (2022). Modeling Business Models: A cross-disciplinary Analysis of Business Model Modeling Languages and Directions for Future Research. *Communications of the Association for Information Systems*. https://doi.org/10.17705/1CAIS.05133

[15] ALICIA – Assembly Lines in Circulation. (2025, March 7) Retrieved from https://cordis.europa.eu/project/id/101091577

[16] Yin, R. K. (2009). *Case study research: Design and methods (Vol. 5)*. Sage.

[17] ISO. ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework. https://www.iso.org/standard/37456.html

[18] Manik, Y., Leahy, J. & Halog, A. (2013). Social Life Cycle Assessment of Palm Oil Biodiesel: A Case Study in Jambi Province of Indonesia. *International Journal of Life Cycle Assessment*, *18* (7), 1386–1392. https://doi.org/10.1007/s11367-013-0581-5

[19] Naghshineh, B., et al. (2020). A Social Life Cycle Assessment Framework for Additive Manufacturing Products. *Applied Sciences*, *10*(13), 4459. https://doi.org/10.3390/app10134459

[20] ISO. ISO 14075:2024 - Environmental management — Principles and framework for social life cycle assessment. https://www.iso.org/standard/61118.html

[21] Mattos, F. & Calmon, J. L. (2023). Social Life Cycle Assessment in Municipal Solid Waste Management Systems with Contribution of Waste Pickers: Literature Review and Proposals for New Studies. *Sustainability*, *15*(2), 1717. https://doi.org/10.3390/su15021717

[22] ISO. ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines. https://www.iso.org/standard/38498.html

[23] Occhipinti, C., et al. (2023). SAT: A Methodology to Assess the Social Acceptance of Innovative AI-Based Technologies. *Journal of Information, Communication and Ethics in Society*, *21*(1), 94–111. https://doi.org/10.1108/JICES-09-2021-0095

[24] Antikainen, M., Uusitalo, T. & Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. *Procedia CIRP*, *73*, 45-49. https://doi.org/10.1016/j.procir.2018.04.027

[25] ISO. ISO 19011:2018 - Guidelines for auditing management systems. https://www.iso.org/standard/70017.html

[26] ISO. ISO 31000:2018 - Risk management — Guidelines. https://www.iso.org/iso-31000-risk-management.html

[27] Becker, S. J., et al. (2023). A Code of Digital Ethics: Laying the Foundation for Digital Ethics in a Science and Technology Company. *AI & Soc*, *38* (6), 2629–2639. https://doi.org/10.1007/s00146-021-01376-w

[28] Van de Poel, I. (2009). Values in Engineering Design. *In Handbook of the Philosophy of Science, Philosophy of Technology and Engineering Sciences,* North-Holland. https://doi.org/10.1016/B978-0-444-51667-1.50040-9

[29] Schwartz, S. H. & Bilsky, W. (1987). Toward A Universal Psychological Structure of Human Values. *Journal of Personality and Social Psychology*, *53*(3), 550–562. https://doi.org/10.1037/0022-3514.53.3.550

[30] Van de Hoven, J. (2017). Ethics for the Digital Age: Where Are the Moral Specs? In: Werthner, H., van Harmelen, F. (eds) *Informatics in the Future*, Springer, Cham. https://doi.org/10.1007/978-3-319-55735-9_6

[31] Khahro, S. H., et al. (2021). A. Risk Severity Matrix for Sustainable Public-Private Partnership Projects in Developing Countries. *Sustainability*, *13*(6), 3292. https://doi.org/10.3390/su13063292

[32] Täuscher, K. & Abdelkafi, N. (2017). Visual tools for business model innovation: Recommendations from a cognitive perspective. *Creativity and Innovation Management*, *26*(2), 160–174. https://doi.org/10.1111/caim.12208

[33] ISO. ISO 14971:2019 - Medical devices— Application of risk management to medical devices. https://www.iso.org/standard/72704.html

[34] Schierlinger-Brandmayr, F., et al. (2021). A Modeling Tool for Exploring Business Ecosystems in a (Pre-)conceptual Phase. In: *Domain-Specific Conceptual Modeling: Concepts, Methods and ADOxx Tools*. Springer, Cham, 315-338. https://doi.org/10.1007/978-3-030-93547-4_14

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Design and Implementation of Soft Robotic Gripper Using 3D Printing Technology

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Abstract: Automated warehouses rely on robotic systems for efficient order picking, yet object manipulation remains challenging due to variations in object shape, size, and material properties. This study focuses on the material selection for the holder of flexible robotic grippers using fused deposition modelling. The holder plays a crucial role in ensuring a secure fit of the gripper's fingers, which is essential for stable and precise object handling in bin picking applications. Testing specimens were fabricated following the ASTM D638-22 standard with a grid infill pattern at full density. Two different variants of Polyethylene Terephthalate Glycol and Acrylonitrile Styrene Acrylate were tested. Mechanical properties, including ultimate tensile strength, elongation at break, and Young's modulus, were estimated using a universal testing machine. Results indicate that one variant of Polyethylene Terephthalate Glycol exhibited the highest tensile strength (40.54 MPa), making it suitable for applications requiring high mechanical strength and resistance to tensile loads, while Acrylonitrile Styrene Acrylate provided a balance between strength and flexibility. These results illustrate the comparison of materials and how material selection and infill density impact the mechanical performance of the holder, which contributes to a better choice of material. Future research will explore the influence of 3D printing temperatures, layer height and testing other infill patterns to further enhance the efficiency and reliability of materials used for robotic grippers in robotic manipulation.

Keywords: intralogistics; robotization; robotic order picking; robotic gripper; tensile strength testing; 3D printing

1 INTRODUCTION

The global warehouse automation market has grown significantly, surpassing $23 billion in 2023 and is projected to reach $41 billion by 2027, driven by the expansion of E-commerce and increasing consumer expectations [1]. As warehouse operations become more complex, logistics providers are integrating automation and robotics to enhance efficiency, flexibility, and productivity [2, 3]. Among these advancements, robotic order picking, particularly bin picking, has gained attention due to its labour intensive nature and the challenges posed by diverse product shapes, sizes, and materials [4, 5].

In E-commerce and Food Logistics, robotic systems must handle a variety of different objects, from fragile products to heavy electronics that require advanced gripping solutions [6, 7]. Picking robots rely on a proper vision system for object recognition and selected robotic grippers for manipulation of objects [8]. Robotic grippers are categorized into rigid and flexible types; while rigid robotic grippers perform well with uniform objects, they struggle with irregular or delicate objects [9]. Soft robotic grippers, which offer adaptability and precision, are increasingly explored for handling fragile and irregularly shaped objects [10].

Advancements in additive manufacturing, particularly Fused Deposition Modelling (FDM), have enabled the rapid development of robotic components, including robotic grippers [11, 12]. A robotic gripper typically consists of a holder, fingers, and actuators for pneumatic or electrical operation [13]. The holder, which connects the robotic gripper to the robotic manipulator, plays a critical structural role. Selecting an optimal material for the holder is essential to ensure mechanical strength, durability, and cost-effectiveness [12].

Polyethylene Terephthalate Glycol (PETG) and Acrylonitrile Styrene Acrylate (ASA) are widely used in 3D printing due to their distinct mechanical properties. PETG offers impact resistance and transparency, while ASA provides high strength and UV resistance, making it suitable for demanding applications [14, 15]. When printed with 100% infill density, these materials exhibit mechanical properties that are crucial for optimizing robotic gripper holders [16].

This study compares the mechanical performance of PETG and ASA for a robotic gripper holder, focusing on tensile strength, elongation at break, and Young's modulus. Specimens were 3D printed following ASTM D638-22 standards [17] and tested to determine their performance. The proposed research aims to answer: How do material type, infill density, and infill pattern affect the mechanical properties of materials, and how can these insights help in selecting the proper materials for developing a holder for a robotic gripper? In summary, this research aims to assess and benchmark different materials for the holder of the robotic gripper by systematically analysing the mechanical properties of 3D-printed samples.

2 LITERATURE REVIEW

The integration of robotic systems in industries such as E-commerce, Healthcare, and Manufacturing has accelerated, particularly in order picking, where robotic grippers play a crucial role [5, 12, 13, 18]. Among them, soft robotic grippers have gained attention due to their adaptability and ability to handle fragile and irregularly shaped objects [18, 19]. Compared to rigid robotic grippers, they offer better compliance and require fewer control complexities, making them more effective in handling diverse warehouse items [19]. However, optimizing the soft robotic gripper design remains a challenge, requiring precise material selection and numerical simulations to check durability and better performance [20].

3D printing, particularly Fused Deposition Modelling (FDM), has been widely adopted for fabricating flexible robotic grippers due to its flexibility in material selection and rapid prototyping capabilities [21]. Recent studies emphasize the role of 3D printing parameters, such as infill density and pattern, in determining mechanical performance [22-24]. Research has shown that infill patterns significantly affect structural integrity, with optimized designs increasing strength up to four times compared to less efficient geometries [23]. However, existing studies largely focus on designing robotic grippers, with limited research on comparing such as material type, infill density, and infill pattern for various materials.

Studies on 3D-printed materials have assessed mechanical properties using standardized methods such as ASTM D638-22 for tensile testing, which evaluates tensile strength, elongation at break, and Young's modulus [17]. Pyka [25] examined eight FDM filaments for biomedical applications, highlighting variations in mechanical behavior, while Georgopoulou [10] explored TPU-based flexible structures with integrated sensors. These findings suggest the need for further research into material-specific behaviours, particularly for industrial robotic applications.

Despite these advancements, research on robotic gripper holders remains limited, particularly in assessing how different 3D printing materials such as PETG and ASA affect mechanical properties under various infill conditions. By analyzing stress, tensile strength, and deformation under standardized testing, our research examines the mechanical properties of different materials to aid in the selection of suitable materials for robotic gripper holders, ensuring enhanced strength and durability for robotic manipulation.

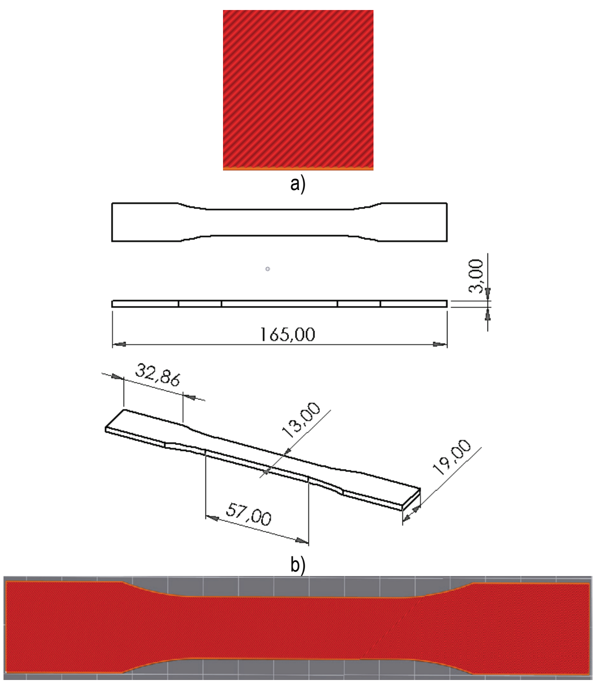

Figure 1 (a) Detailed view of the infill, (b) Geometry of the 3D printed specimen (measurements in mm), and (c) Slicing profile of the 3D printed specimen.

3 METHODOLOGIES

3.1 Specimen Preparation

To ensure mechanical comparability, all specimens were printed at 100% infill density using a grid pattern. ASA (Prime Natural) and PETG (Transparent and Original Lipstick Red) were selected as experimental materials. Based on manufacturer guidelines, a 0.4 mm nozzle and a printing temperature of 250 °C were applied uniformly for all samples. All samples were printed according to the ASTM D638-22 standard [17] in the form of dog bone-shaped specimens. A grid was used as the filling pattern. Fig. 1 illustrates the specimen geometries, dimensions (in mm), and slicing profiles.

The slicer used for printing the specimens was Creality Print V5.1 to generate the G-code, with settings based on the printer manufacturer's recommendations [26] and prior research to ensure consistent mechanical properties and reliable printing quality [27]. Tab. 1 lists the main 3D printing parameters used to produce samples with a grid fill pattern. The layer height was maintained at 0.24 mm, while the first layer was printed at a slightly lower height of 0.2 mm to enhance bed adhesion. The printing speed was set at 70 mm/min to balance precision and efficiency, while the printing bed temperature was maintained at 60 °C to ensure proper adhesion and minimize warping.

Table 1 Printing parameters used for fabrication testing samples

Parameter	Value
Nozzle diameter	0.4 mm
Print temperature °C	250
Layer height	0.24 mm
First layer height	0.2 mm
Infill density	100%
Infill pattern	Grid
Printing speed	70 mm/min
Printing bed temperature	60 °C

3.2 Equipment's Used

The specimens were printed using the Creality K1 Max [28] with parameters. As shown in Tab. 1, the parameters were set according to the manufacturer's recommendations and matched with the printer settings. The printer is equipped with a 0.4 mm nozzle and has maximum nozzle temperatures of 230 °C for TPU and 250 °C for the other materials. In total, three specimens were printed following ASTM D638-22 standards. Tensile testing was conducted using the Zwick Roell Vibrophore 100, where key mechanical properties including ultimate tensile strength, elongation at break, and Young's modulus were evaluated. These properties were chosen because ultimate tensile strength indicates the maximum load the material can bear, elongation at break reflects its ductility and deformation behaviour, and young's modulus provides a measure of its stiffness. Collectively, these metrics offer critical insights into the robotic gripper holder's performance, ensuring that it can withstand operational stresses without failure or excessive deformation [29].

3.3 Experimental Setup

For the preparation of the specimens, 2 materials were used: PETG and ASA. The 3D printing parameters, including infill density, printing temperature, and infill pattern, were carefully selected to ensure optimal mechanical performance. This approach allows for the evaluation of the most suitable material for the soft robotic gripper's holder. For preliminary testing, a single specimen per material was printed and tested. This allowed for an initial assessment of mechanical properties before conducting a larger-scale statistical analysis. Future studies will include at least three specimens per material to improve accuracy and minimize variability. The CAD model for the specimen was designed using SolidWorks 2024 software, following ASTM D638-22 Type I tensile test standards. The specimen used and the image for the printed samples are shown in Fig. 2.

Figure 2 Printed specimens for the tensile test

For the preparation of the experiment and to ensure accurate results presented in Tab. 3, the measurement data for the width and thickness of each specimen were calculated for each material.

Table 2 Measurement data for the specimens

Sample name	Material type	Width (mm)	Thickness (mm)
030111	PETG Original Lipstick Red	13.2	3.00
030211	PETG Transparent	12.99	3.01
040011	ASA Prime Natural	12.57	2.97

Tab. 2 shows the sample names, materials used, and dimensions of each specimen, with width and thickness measurements calculated individually to account for variations and ensure accuracy.

4 RESULTS AND ANALYSIS

The geometry of the tensile specimens was designed in SolidWorks 2024 in accordance with the standard test method for tensile strength of plastics (ASTM D638-22) [17]. Specimens were tested using a Zwick Roell Vibrophore 100 universal testing machine [29]. The Vibrophore 100 is a high-frequency testing machine that can perform both dynamic and static material tests and has a load capacity of 100 kN [30]. The testing system was configured with testXpert III software, which automatically recorded the test data and generated graphical results. The most important parameters measured during the tests were the ultimate tensile strength (MPa), the yield strength (MPa) and the test duration (seconds).

During the tensile tests, a strain extensometer was used to accurately measure the deformation (strain) of the individual specimens [31]. An extensometer was attached to the specimen mounted on the Vibrophore 100. It tracked the change in length as the applied load increased. This precise measurement of strain is essential for the calculation of mechanical properties such as modulus of elasticity, yield strength and elongation at break. The extensometer ensured that the recorded data reflected the true behaviour of the material and reduced errors that could occur if displacement were measured only at the grips [32]. The testXpert III software was configured with the initial test parameters to achieve accurate results. The tests were conducted under controlled laboratory conditions at a room temperature of approximately 20 °C, with small variations of ±1–2 °C. The graph on Fig. 4 presents the experimental results, comparing standard stress (MPa) and strain (%).

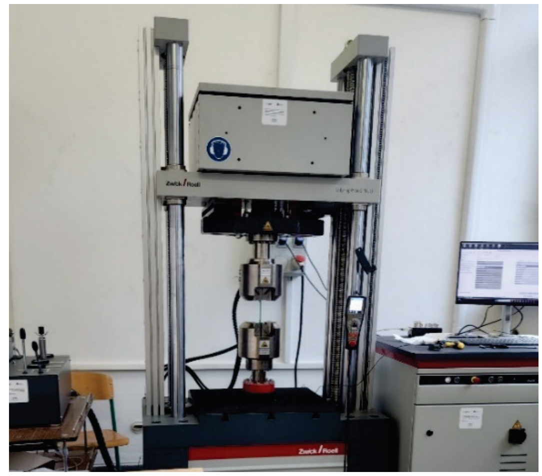

Figure 3 Tensile tests performed in the laboratory to evaluate the mechanical properties of the tested materials. The setup includes a universal testing machine applying controlled tensile forces while measuring elongation and stress response

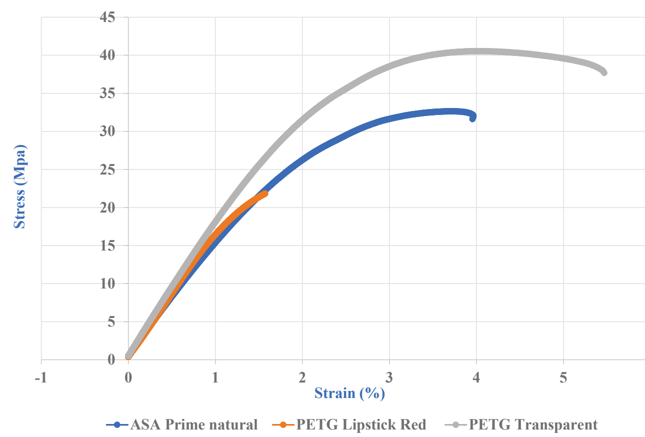

Figure 4 A graphical representation of the tensile test results for the materials tested (ASA Prime Natural, PETG Original Lipstick Red, and PETG Transparent)

The stress-strain curves on Fig. 4 illustrate the mechanical differences between the tested materials. The *x*-axis represents strain (%), which is the elongation normalized by the original length, while the *y*-axis represents stress (MPa), which is the applied force divided by the measured cross-sectional area. PETG original lipstick Red (orange curve on Fig. 4) shows lower tensile strength and a lower strain at fracture, indicating brittle behaviour. PETG Transparent (grey curve on Fig. 4) exhibits higher stress and strain or elongation, making it more ductile and mechanically superior. ASA Prime Natural (blue curve on Figure 4) exhibits lower strain than PETG Transparent but higher than PETG Original Lipstick Red, with strength values between the two, indicating a moderate balance between strength and flexibility.

The tabular results, automatically generated by the testXpert III software, provide the $Rp_{0.2}$, and Rm (yield strength and ultimate tensile strength in MPa), as shown in Tab. 3.

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Table 3 Table 3 presents the experimental test results

Material	Yield Strength (MPa)	Ultimate Strength (MPa)
ASA Prime natural	21.03	21.83
PETG Transparent	29.76	40.54
PETF original lipstick red	20.76	27.84

Tab. 3 shows that PETG Transparent had the highest yield strength (29.76 MPa) and ultimate tensile strength (40.54 MPa), indicating its superior mechanical strength compared to the other materials tested. ASA Prime Natural exhibited moderate values ($Rp_{0.2}$ = 21.03 MPa, Rm = 21.83 MPa), while PETG Original Lipstick Red had the lowest values ($Rp_{0.2}$ = 20.76 MPa, Rm = 27.84 MPa), suggesting lower resistance to tensile forces.

However, factors like instrument accuracy, operator variability, and environmental conditions (e.g., temperature and humidity) could introduce measurement uncertainties. Future experiments could improve reliability through multiple trials, machine calibration, and controlled environments. The manufacturer-provided data for the tested 3D printing materials includes values for yield strength, tensile strength, and tensile modulus. For ASA Prime Natural, the yield strength is 30.1 MPa, tensile strength is 37.6 MPa, and tensile modulus is 2100 MPa. Both PETG Transparent and PETG Original Lipstick Red have identical values for yield strength (37.5 MPa), tensile strength (56.7 MPa), and tensile modulus (2100 MPa) for the former and 1900 MPa for the latter [26]. The test results obtained did not include tensile modulus E, but tensile modulus was determined by calculating the tangent of the linear portion of the stress-strain curve and compared with the manufacturer's specifications. A comparison between the tensile modulus values obtained from our tests and the manufacturer-provided data for the 3D-printed specimens reveals significant relative deviations. The relative deviation was calculated based on the standard statistical definition for standard deviation [35]. PETG Transparent (030211) exhibited a tensile modulus of 1800 MPa, with only a 5.26% relative deviation from the manufacturer's value of 1900 MPa.

Table 4 Manufacture data with tensile, yield strength and tensile modulus (E)

Material	Calculated tensile modulus (MPa)	Tensile modulus from manufacturer data (MPa)	Relative deviation (%)
PETG (Original Lipstick Red)	1750	2100	–16.67%
ASA (Prime Natural)	1500	2100	–28.57%
PETG (Transparent)	1800	1900	–5.26%

PETG Original Lipstick Red (030111) showed a tensile modulus of 1750 MPa, 16.67% lower than the expected 2100 MPa. The most significant discrepancy was seen in ASA Prime Natural (040011), where the tensile modulus was 1500 MPa, a 28.57% relative deviation from the expected value.

These differences may be due to factors such as incorrect 3D printing parameters, layer height, environmental conditions during testing or inherent material inconsistencies [23]. The smaller relative deviation in PETG suggests it keeps its strength well during testing. In contrast, the higher relative deviation in ASA might show that it's more affected by 3D printing settings like print speed, temperature, and layer height. Future investigations into the influence of printer settings and infill patterns could provide further insight into these relative deviations. Overall, the experimental results indicate that the 3D-printed ASA and PETG samples exhibited lower mechanical properties than the manufacturer's values, with PETG Original Lipstick Red showing the most significant reductions. PETG Transparent performed better, with a tensile modulus closest to the expected value, while ASA Prime Natural had the largest relative deviation.

During the initial phase of testing materials for the holder of the robotic gripper, the results showed variability compared to the manufacturer's provided data. The discrepancies can be attributed to several factors, including the incorrect printer settings and printing temperature, infill pattern, specimen design, and material properties. For instance, selecting an appropriate infill pattern, such as a line pattern, could have improved the consistency of mechanical properties. Additionally, testing multiple samples with different infill patterns (lines) and in different infill orientations such as latitudinal, transverse, and inclined orientations would have provided a more comprehensive understanding of the material's behaviour. To enhance the accuracy and reliability of the results, future research should involve testing a broader range of samples and materials under varied conditions.

5 CONCLUSIONS

This study investigated the mechanical properties of 3D printed materials (PETG and ASA) for the holder of the robotic gripper. The results showed that PETG Transparent had the highest tensile strength (40.54 MPa) and yield strength (29.76 MPa), making it the most robust material for applications requiring high mechanical performance. ASA Prime Natural showed moderate strength, while PETG Original Lipstick Red showed lower tensile strength, indicating that it is more suitable for less demanding tasks.

The relative deviations between experimental results and manufacturer data, particularly in tensile modulus, highlight the influence of 3D printing parameters, such as layer adhesion and infill patterns, on material performance. These findings emphasize the need for optimized printing conditions to achieve mechanical properties closer to theoretical values.

According to findings from [23], printing temperature and infill orientation significantly affect tensile strength and modulus. Although our study employed only a single combination of printing parameters, the observed deviations from the manufacturer-provided mechanical properties suggest that factors such as layer height, printing temperature, and infill patterns could be responsible. While a systematic parametric study was not performed, the discrepancy indicates that suboptimal or non-standard settings may have influenced the results, consistent with findings in the literature. Research suggests that using a line infill pattern with longitudinal, transverse, and inclined orientations improves material strength and consistency. This comparison confirms that printing parameters play a key role in mechanical performance.

5.1 Future Work

Future research should examine how different printing parameters, such as temperature, velocity, print orientation, and nozzle orientation, affect print quality. It is also recommended to print with a single or double outer layer (commonly referred to as the 'shell') to achieve accurate and consistent mechanical results, as the number of outer walls can significantly influence the structural integrity, tensile strength, and durability of the printed part. This approach was also adopted by [23] in their study on the influence of infill parameters on mechanical properties. Material selection is also important, considering factors like strength, flexibility, durability, and resistance to environmental conditions. The selected material, whether PETG or ASA, should meet the specific needs of the robotic gripper.

Based on previous research, ensuring accurate and reliable testing requires adherence to ISO standards, such as ISO 527 [33] and ISO 178 [34] . Testing should include proper material drying before the experiment, controlled cooling after the experiment, and conducting at least three to five repetitions to account for variations and ensure accurate results.

For improved mechanical performance, future studies may consider exploring full range of recommended printing bed and nozzle temperatures, as higher temperatures can enhance interlayer bonding and reduce voids when properly controlled. However, this should be validated experimentally, as the optimal settings may vary depending on the material and printer. Printing speed of up to 300 mm/s, and assess the impact of different printers, slicers, and cooling levels (fan settings based on material manufacturer recommendations) should be considered. These findings will help develop strong and reliable holders of robotic grippers while showing the potential of 3D printing for cost-effective and customized components for robotic manipulation.

6 REFERENCES

[1] Statista. (2023). *Size of the warehouse automation market worldwide from 2023 to 2027*. Statista. https://www.statista.com/statistics/1094202/global-warehouse-automation-market-size/

[2] Iftekar, S. F., Aabid, A., Amir, A., & Baig, M. (2023). Advancements and limitations in 3D printing materials and technologies: A critical review. *Polymers, 15*(11), 2519. https://doi.org/10.3390/polym15112519

[3] Desai, S. M., Sonawane, R. Y., & More, A. P. (2023). Thermoplastic polyurethane for three-dimensional printing applications: A review. *Polymers for Advanced Technologies, 34*(7), 2061-2082. https://doi.org/10.1002/pat.6041

[4] Boysen, N., De Koster, R., & Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. *European Journal of Operational Research, 277*(2), 396-411. https://doi.org/10.1016/j.ejor.2018.08.023

[5] Bencak, P. (2023). *Object detection and graspability analysis for robotic bin-picking application in intralogistics*. https://plus.cobiss.net/cobiss/si/sl/bib/154849795

[6] Brown, A. S. (n.d.). Amazon's robot arms break ground in safety and technology. *Amazon Science*. https://www.amazon.science/latest-news/amazon-robotics-see-robin-robot-arms-in-action

[7] Foodics. (n.d.). *Rise of robotics in the food industry: Pros, cons, and application*. https://www.foodics.com/robotics-in-the-food-industry/

[8] Bencak, P., Hercog, D., & Lerher, T. (2023). Simulation model for robotic pick-point evaluation for 2-F robotic gripper. *Applied Sciences, 13*(4), 2599. https://doi.org/10.3390/app13042599

[9] Terrile, S., Argüelles, M., & Barrientos, A. (2021). Comparison of different technologies for soft robotics grippers. *Sensors, 21*(9), 3253. https://doi.org/10.3390/s21093253

[10] Georgopoulou, A., Vanderborght, B., & Clemens, F. (2021). Fabrication of a soft robotic gripper with integrated strain sensing elements using multi-material additive manufacturing. *Frontiers in Robotics and AI, 8*, 615991. https://doi.org/10.3389/frobt.2021.615991

[11] Ahn, S.-J., Lee, H., & Cho, K.-J. (2024). 3D printing with a 3D printed digital material filament for programming functional gradients. *Nature Communications, 15*(1), 3605. https://doi.org/10.1038/s41467-024-47480-5

[12] Blanco, K., Navas, E., Emmi, L., & Fernandez, R. (2024). Manufacturing of 3D printed soft grippers: A review. *IEEE Access, 12*, 30434-30451. https://doi.org/10.1109/ACCESS.2024.3369493

[13] Patil, V., Narnaware, T., Gangwani, N., & Raykar, N. R. (2020). Development of flexible universal gripper for handling light weight parts of arbitrary shape. *Materials Today: Proceedings, 28*, 2591-2598. https://doi.org/10.1016/j.matpr.2020.05.705

[14] Ahmed, I., Sullivan, K., & Priye, A. (2022). Multi-resin masked stereolithography (MSLA) 3D printing for rapid and inexpensive prototyping of microfluidic chips with integrated functional components. *Biosensors, 12*(8), 652. https://doi.org/10.3390/bios12080652

[15] Tamașag, I., Beșliu-Băncescu, I., Severin, T.-L., Dulucheanu, C., & Cerlincă, D.-A. (2023). Experimental study of in-process heat treatment on the mechanical properties of 3D printed thermoplastic polymer PLA. *Polymers, 15*(10), 2367. https://doi.org/10.3390/polym15102367

[16] Heidari-Rarani, M., Ezati, N., Sadeghi, P., & Badrossamay, M. (2022). Optimization of FDM process parameters for tensile properties of polylactic acid specimens using Taguchi design of experiment method. *Journal of Thermoplastic Composite Materials, 35*(12), 2435-2452. https://doi.org/10.1177/0892705720964560

[17] ASTM. (2022). *Standard test method for tensile properties of plastics – ASTM D638-22*. https://www.astm.org/standards/d638

[18] Goh, G. D., Agarwala, S., Yeong, W. Y., et al. (2022). 3D printing of robotic soft grippers: Toward smart actuation and sensing. *Advanced Materials Technologies, 7*(11), 2101672. https://doi.org/10.1002/admt.202101672

[19] Xin, Y., Zhou, X., Bark, H., & Lee, P. S. (2024). The role of 3D printing technologies in soft grippers. *Advanced Materials, 36*(34), 2307963.

https://doi.org/10.1002/adma.202307963
[20] Păcurar, R. I., Tănase, G., Mihai, F., Gherghin, R., Deaconescu, A., & Deaconescu, T. (2024). Use of high-performance polymeric materials in customized low-cost robotic grippers for biomechatronic applications: Experimental and analytical research. *Frontiers in Materials, 11*, 1304339. https://doi.org/10.3389/fmats.2024.1304339
[21] Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X., & Whitesides, G. M. (2011). Soft robotics for chemists. *Angewandte Chemie International Edition, 50*(8), 1890-1895. https://doi.org/10.1002/anie.201006464
[22] Lopes, L., Reis, D., Paula Junior, A., & Almeida, M. (2023). Influence of 3D microstructure pattern and infill density on the mechanical and thermal properties of PET-G filaments. *Polymers, 15*(10), 2268. https://doi.org/10.3390/polym15102268
[23] Khaliq, J., Gurrapu, D. R., & Elfakhri, F. (2023). Effects of infill line multiplier and patterns on mechanical properties of lightweight and resilient hollow section products manufactured using fused filament fabrication. *Polymers, 15*(12), 2585. https://doi.org/10.3390/polym15122585
[24] Nace, S. E., Tiernan, J., Holland, D., & Ni Annaidh, A. (2021). A comparative analysis of the compression characteristics of a thermoplastic polyurethane 3D printed in four infill patterns for comfort applications. *Rapid Prototyping Journal, 27*(11), 24-36. https://doi.org/10.1108/RPJ-07-2020-0155
[25] Pyka, D., Karpiński, R., Marciniak, D., Rojek, I., Wichniarek, R., Zawadzki, P., & Budzik, G. (2024). Research on basic properties of polymers for fused deposition modelling technology. *Applied Sciences, 14*(23), 11151. https://doi.org/10.3390/app142311151
[26] Azure Films. (n.d.-a). *Technical data sheets*. https://azurefilm.com/sl/technical-data-sheets/
[27] Azure Films. (n.d.-b). *Technical data sheets listi*. https://azurefilm.com/sl/technical-data-sheets/
[28] Creality. (n.d.). *K1 Max*. https://www.creality.com/products/creality-k1-max-3d-printer
[29] ZwickRoell. (n.d.-a). *Product information ZwickRoell Vibrophore 100*. https://www.zwickroell.com/fileadmin/content/Files/SharePoint/user_upload/PI_EN/13_890_Vibrophore_100_PI_EN.pdf
[30] RiUM. (n.d.). *High frequency testing machine*. https://cvu.fs.um.si/raziskovalna-oprema/posamezna-oprema/visokofrekvencni-preizkusni-stroj
[31] ZwickRoell. (n.d.-b). *Extensometer categories*. https://www.zwickroell.com/accessories/extensometers/
[32] Epsilon Technology Corp. (n.d.). *What is an extensometer? Basic extensometer guide*. https://www.epsilontech.com/extensometer-basics/
[33] ZwickRoell. (n.d.-c). *Tensile test on plastics ISO 527-1 | ISO 527-2*. https://www.zwickroell.com/industries/plastics/thermoplastics-and-thermosetting-molding-materials/tensile-test-iso-527-1-2/
[34] ISO. (2019). *ISO 178:2019 – Plastics — Determination of flexural properties*. https://www.iso.org/standard/70513.html
[35] Wan, X., Wang, W., Liu, J., et al. (2014). Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Medical Research Methodology, 14*, 135. https://doi.org/10.1186/1471-2288-14-135

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Regulatory Compliance and Innovation: A Literature Analysis on the Impact of Sustainability Legislation on Engineering and Supply Chain Innovations by the Example of the German Circular Economy Act

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Abstract: This paper examines the effects of sustainability laws on innovation, with a particular focus on the German Circular Economy Act. The study investigates whether strict environmental regulations promote technological advances and sustainable business practices. The results show a differentiated picture. While the German Circular Economy Act and similar regulations encourage companies to adopt resource-efficient practices, the level of innovation varies significantly between industries. Industries such as packaging and high technology are showing remarkable progress, including the development of sustainable materials and optimized product designs for recycling and repair. In contrast, challenges such as high initial costs, technological complexity and regulatory uncertainties make it difficult to innovate, especially for small and medium-sized enterprises. In addition, supply chain innovations are often consistent with lean management principles, which shows how regulatory frameworks can contribute to leaner processes and a reduction in waste.

Keywords: circular economy; innovation; regulatory compliance; resource efficiency; supply chain management; sustainability

1 INTRODUCTION

The past few years have seen an increase in the number of environmental, social and governance (ESG) laws and regulations being adopted around the world. There has been a reported 155% increase in the number of regulations enacted in the current decade compared to all previous decades [1]. However, their effectiveness and usefulness is still being debated and not only questioned but scrutinised by politicians, the public and economists [2].

Over the past decade, several pieces of legislation have been passed for example by the European Union (EU) with a clear determination to implement a more sustainable way of living. This is particularly important as the EU is one of the world's biggest polluters per capita. Nonetheless, politicians and entrepreneurs still believe the amount of regulations is impeding innovation and that the free market would handle sustainability and the circular economy much better without government intervention [3].

This paper will analyse the implementation of sustainability laws and their impact on innovations in supply chain management and engineering, using the German Circular Economy Act as an example. Finally, the paper will prove or disprove the hypothesis if "sustainability legislation has a positive impact on sustainability and related innovations". In addition, the paper will discuss challenges and solutions companies face when implementing circular economy laws and strategies.

2 METHODOLOGY

The methodology of the paper is based on a systematic literature review, which is an essential part of any scientific work. The literature was obtained by searching the university's own research tool BOSS, as well as the website Google Scholar. While Google Scholar was generally used with keywords relevant to the topic and chapters, the BOSS research tool allowed for a more precise search. In this system, the authors specified keywords, a publication period and that the papers listed should be peer-reviewed. This was the first step in the filtering process of relevant literature.

To ensure the quality of the papers, the German VHB Jourqual 3 and the Resurchify website were used to check the journals in which the selected papers appeared. The VHB Jourqual has its own ranking system in the form of letter grades, from the best with "A+" to the worst with "D". For this paper, all journals ranked from "A+" to "C" were considered as high qualitative literature. Additionally, the Resurchify website was used based on the corresponding H-index to integrate all international journals due to the fact that not all journals are listed in the VHB Jourqual [4].

3 CONCEPTUAL FRAMEWORK OF REGULATORY COMPLIANCE AND CIRCULAR INNOVATION

3.1 Regulatory Compliance

At its most basic, compliance is the act of obeying laws and regulations set by governments. These can be governing bodies at different levels, for example local, national or international. Failure to comply with regulations may result in some form of penalty. These penalties can take different forms and are often influenced by the governing body, the content of the legislation and the people affected by the rule.

A well-known distinction of laws is the soft law to hard law scale. Soft Laws are often brought to existence by a group of people or institutions agreeing to something and possibly signing something to show their public commitment, but if the participants choose to disregard these guidelines, there is no prosecution or penalty, apart from possible public outrage. Examples are the United Nations Sustainable Development Goals or the Paris Climate Agreement [5, 6].

On the other hand, hard laws are issued by bodies that have an executive. Failure to obey and comply with these laws will result in different levels of consequences. These laws are also less open to interpretation, meaning that their purpose is much clearer and examples are given. The consequences may vary, some may be of a monetary nature, and others may exclude companies from governing body's projects, such as for example invitations to tender. In the most extreme cases, it can result in a prison sentence for the person responsible [6].

Another consequence of hard law, similar to soft law, is a loss of reputation. Many large companies in the EU and around the world already recognise corporate social responsibility and publish information about their own businesses and initiatives. Going against their written word would affect the interests of shareholders and stakeholders, which most companies prefer to avoid if possible [7].

3.2 Circular Economy and Circular Innovation

The concept of circular economy has been defined on numerous occasions throughout the last decade, most notably by the Ellen MacArthur Foundation. They characterise the circular economy as a system in which all materials and products are retained within a continuous cycle, through the implementation of maintenance, recycling and composting practices. The objective of a circular economy is to combat climate change and transform the economic system, by decoupling it from the consumptive use of finite resources [3, 8-12].

A literary summary of 117 different definitions, describes circular economy comprehensively as: "An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers); meso level (eco-industrial parks) and macro level (city, region, nation and beyond); with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers [13]."

On official level, the EU defines circular economy as: "A system which maintains the value of products, materials, and resources in the economy for as long as possible, and minimises the generation of waste. This means a system where products are reused, repaired, remanufactured, or recycled [14]."

Following the definition of circular economy, circular innovations can be described as innovations focused on closing the consumption loop, extending the product lifecycle and reducing energy consumption. Circular innovations aim at sustainable development through the lens of the economic, social and environmental dimensions of sustainability [8, 11, 15-18].

The Porter hypothesis is a frequently employed theoretical framework in current research, as it continues to offer insights relevant to contemporary contexts. The hypothesis maintains that the implementation of precise and unyielding environmental regulations can lead to an influx of efficiency and innovations, fostering a more competitive market and resulting in a positive economic effect. Despite occasional criticism, e.g. from Cohen and Tubb 2018 [19], the Porter hypothesis has been utilized as the basis for numerous scientific papers, including this one, and has also been applied in policy-making [15-17, 20].

4 THE GERMAN CIRCULAR ECONOMY ACT

4.1 General Overview of the German Circular Economy Act

Germany has enacted numerous legislation initiatives with a focus on sustainability, many of which have been derived from the EU. One of the most important regarding the implementation of circular economy is the German Circular Economy Act, which is grounded in a multitude of EU directives, most notably Directive 2008/98. The directive was published in November 2008 and was scheduled for adaptation into national law by the end of 2010. Subsequently, in 2018, the directive was expanded and updated in the light of the introduction of the EU Circular Action Plan, which set out a series of objectives designed to ensure accountability at the EU level [21].

The objective of the directive was to establish a waste hierarchy, which provides a descending classification and regulatory framework for the management and treatment of waste. The primary objective – level one – is the prevention of waste. This encompasses the utilisation of more intelligent engineering methodologies that are designed with the objective of reducing waste. The second level is the reuse of material in the after-use-phase of products, which also encompasses the application of intelligent engineering and enhanced supply chain management. The third level is the recycling of waste, whereby the material is separated into its original components and processed to become a new resource. The waste is recovered for alternative purposes [3, 17, 22].

Therefore, the German Circular Economy Act is mostly talking about recycling and recovery to avoid to talk only about overconsumption and implement a more radical use and implementation of the so called ten Rs, which are an expansion of the popular three Rs, known as reuse, reduce and recycle [17].

R0 to R2 are focused on a general mind change through refusal, rethinking and reducing. Even simple changes can lead to a lower resource consumption. This could include the refusal of a plastic bag at the store, bringing one's own silverware instead of using disposable cutlery, or simply ordering less takeout food as an end consumer. Similarly, companies can change their ways of thinking and easily minimize the number of resources used and the amount of waste created.

R3 to R7 include the following aspects in chronological order: reuse, repair, refurbish, remanufacture and repurpose. The thought behind these steps is to extend the lifecycle of the final product or its parts. Companies have to reconsider the final product design already at the beginning of the development process to ensure sustainable solutions at the end of its lifecycle.

R9 and R10 are focused on recycling and recovery. In this context, components are disassembled into their base materials and repurposed accordingly. The use of waste for energy recovery through incineration is only seen as the last possible option, as it does not reintroduce the material back into the cycle [3, 17].

4.2 Case Studies Illustrating the Implementation of the German Circular Economy Act

The following five case studies from different industries in Germany demonstrate alternative ways to implement the German Circular Economy Act.

Case one – New packaging: a large packaging producer and manufacturer of packaging machines decided to use a more radical approach by developing innovative packaging materials. The new packaging concept was developed following the implementation of the new law and the global popularisation of circular economy [10].

Case two – Lifetime extension through regeneration: a company using industrial catalysts decided to lessen their risk of partaking in a highly volatile market by reusing the materials multiple times. Industrial catalysts use metals from the platinum group, meaning the material is a by-product of another raw material, making the market extremely dependant from the main material. Palladium and other platinum metals are also mined in countries that are known for high export taxes, making the market for these materials even more uncomfortable [23].

Case three – Less packaging: a well-known grocery chain in Germany decided as part of circular economy strategy to reduce the amount of packaging. This was done by removing all plastic packaging on single products, leaving only a small sticker for the recognition of the product. They also encouraged customers to bring their own reusable bags by not offering free plastic bags anymore [24].

Case four – Recycling of material: multiple jet engine manufacturers use rhenium in their superalloys for jet engines and other components. Since rhenium is a by-product of molybdenum, the market revolves around the market for molybdenum, making the sourcing very difficult. Once circular economy became more known and viable, the manufacturers started to optimize their processes to reduce material losses and to recover the rhenium from older products and reuse it [23].

Case five – Extension of life through a new business model: a well-established appliance manufacture, which previously did only focus on business to business sales, introduced a new leasing option for business to consumer sales. To ensure the financial viability of this leasing option, the appliances needed to remain durable enough to serve multiple clients. As a result, the company extended the lifespan of their manufactured products [10].

5 THE IMPACT OF SUSTAINABILITY LEGISLATION ON ENGINEERING INNOVATIONS

Engineering nowadays, includes a variety of specialized areas, such as the design and enhancement of infrastructure, machinery, vehicles, electronic devices, materials, and energy systems [25].

As previously stated, case one is focused on the introduction of new packaging materials. The company chose to invest in a start-up with the objective of developing a material to be used as an alternative to the company's existing packaging options. The start-up was already engaged in the development of a paper packaging solution that was distinguishable from the options offered by the parent company, which predominantly utilized plastic packaging. The start-up was granted permission to retain its entrepreneurial structure, allowing it to engage external personnel when necessary to acquire expertise and perspective [10].

In case four the production process was optimised and rhenium was recovered through disassembly. Hereby, one of the main engineering challenges was the designing of components with their post-use lifecycle in mind. This was done to avoid unnecessary costs connected to the disassembly and recycling of materials. In addition to modify the parts for enhanced disassembly, it was also necessary to ensure that the product could be repaired in a cost-effective way, thereby extending its operational lifecycle, similar to case five. In this case, the implementation of circular economy strategies has resulted in notable benefits for the manufacturer while simultaneously creating a positive environmental impact [10, 23].

Case two is the final example of engineering changes and corresponding innovations. To reduce their dependency on the platinum metals market, these industrial catalyst users initiated a regeneration process, making it possible to recycle the rare earth elements. In essence, a previously unused process was established to remove carbon coatings, significantly extending the product's lifecycle and creating a closed loop for the catalysts, thereby effectively enforcing a circular economy.

All these measures are not solely driven by regulatory compliance. By implementing these innovative processes, companies can achieve a more resource-efficient operation, leading to a range of benefits, including reduced material costs [23].

Studies showed that circular economy can most effectively be implemented through radical changes within a company. Start-ups often take the lead as frontrunners, driven by radical ideas that have the potential to disrupt the markets they enter. What start-ups are often missing is capital. Similarly, large companies have the capital, but they often cannot implement radical innovations, as they are not accepted within the organization. This situation leads to collaborative measures. Large corporations often acquire start-ups, letting them continue their quest to innovate. Once the start-up's solution is well-established, the corporation can integrate it across the whole organization, gaining a significant competitive advantage [10, 11].

The implementation of circular economy forces companies to invest in applicable procedures, as these often go hand in hand with cost efficiency. This approach enables businesses to operate in a more risk averse and independent manner, such as through the reuse of rare earth elements.

Hereby, manufacturers reduce their reliance on external markets and mines by using their own reserves during periods of scarcity and peak prices [23].

Furthermore, political initiatives by the EU to fight climate change significantly influenced material pricing. New resources and recycled materials now have almost the same price, whereas recycled materials were far cheaper before. This shift has reduced the financial risk for companies opting for resource-efficient options [3].

6 THE IMPACT OF SUSTAINABILITY LEGISLATION ON SUPPLY CHAIN INNOVATIONS

A supply chain describes an interwoven network of moving materials, parts, and products from the creation level to the end consumer [26]. Many circular economy strategies focus on a leaner supply chain by optimizing the corresponding products and processes. A leaner management approach is caused by the removal of inefficient and wasteful parts in the supply chain [8].

In case three, a popular grocery store in Germany decided to remove all plastic packaging on single products and replace it with identification stickers where necessary. This allows the product to bypass an additional stop before reaching the grocery store, reducing transport distances and enabling the use of more regional products, as they no longer needed to be sent to an external packaging facility. This created a more direct supply from the farmer, without the use of any intermediaries. Favourably, with respect to the Circular Economy Act, the grocery chain generated less waste for which they were accountable as face to the end costumer. The use of new packaging solutions optimised the supply chain and created a leaner flow with no negative impact on the customer side [24].

A further example of an organisational adaptation to circular economy is the introduction of a new business model in case five. A new unit was established to drive innovation beyond the traditional activities and encourage a more creative problem-solving. One initiative was the development of a leasing option for the company´s appliances. Previously, sales were limited to a business-to-business model, but the new leasing model introduced a business-to-consumer solution, enabling the firm to engage directly with the end customers. To ensure economic viability, appliances were designed for easy repairs, as the leasing offer included repairs and replacements. The most significant benefit was for the end consumers, as middlemen were eliminated, allowing direct communication with the manufacturer. Furthermore, the leasing system led to a superior product quality for the end customers [3, 10, 13].

As previously discussed, two of the cases presented in this paper focused on the implementation of circular economy strategies connected to rare earth elements. In addition to the engineering innovations required for recycling these metals, the innovations also led to improvements in the supply chain conditions for the companies. As a consequence, the companies were less dependent on the timely sourcing of materials, thereby affording them higher levels of negotiation power. Consequently, the companies were able to select their suppliers and plan more effectively, rather than being entirely at the mercy of the metal market. This results in more advantageous supply chain management options and opportunities, which are financially beneficial to the companies [23].

The implementation of innovative practices within the supply chain can be a highly advantageous strategy for businesses, providing them with a competitive advantage in their respective marketplaces. As the global scope of supply chains expands, the number of competitors rises accordingly. The implementation of effective supply chain management strategies ensures the consistent and reliable supply of materials, parts, and finished products in order to meet the customer demand. In times of global distress, such as global pandemics, wars or natural catastrophes, a reliable supply chain is the most important for a company's survival [23].

Nevertheless, modifications to supply chain networks have the potential to result in dissatisfaction among suppliers. If a company identifies a step in its process that does not add value to the product or service, the supplier responsible for that step is removed from the supply chain. Such actions result not only in the alienation of business partners, but also in a reduction in business for the supplier. Should other companies adopt a similar approach, the supplier may be forced into bankruptcy [10, 24].

These disruptive measures are often to extreme for many companies, leading to only incremental changes. This slows the full adoption of circular economy, as companies frequently fail to reach the final stages of implementation before reverting to previous practices. Achieving these changes requires a fundamental shift in the approaches [10].

The implementation of circular economy practices in the EU has led to the mainstreaming of reverse logistics and reverse supply chain practices, creating a novel market for logistics services to meet the need for the retrieval of products. The concept gained popularity within the rise of circular economy, particularly with the adoption of the "polluter pays" principle [3, 10, 13].

7 KEY DRIVERS OF INNOVATION ADOPTION AND REGULATORY COMPLIANCE

The following chapter will examine the factors that influence the decision-making processes of companies with regard to the adoption of innovative practices in the context of circular economy.

The majority of companies only comply with regulations to avoid penalties or other forms of punishment. Many companies avoid taking the additional step of innovating, as it requires significant investments in labour and capital for research and development – costs that often exceed their financial capabilities. The result is that companies tend to implement only the minimum necessary to comply with the relevant regulations, as the economic benefits of circular economy innovations are often not deemed significant enough to justify greater investment [8].

One of the most significant factors influencing the implementation of circular economy legislation is public perception. A company’s primary objective is to meet market demands. However, circular economy operates on a belief system that may not align with traditional business priorities. Moreover, the belief system has been regarded as less pertinent by the general public since the Covid-19 pandemic. During the pandemic, single-use items regained popularity as fear of the virus reached its peak, contradicting the principles of circular economy [22].

Another factor contributing to the reluctance of companies to progress is the internal disruption that often occurs when implementing circular economy strategies. The need for a change in company values and visions can be challenging to address. The complexity of change management can lead to difficulties in maintaining sustainable solutions in the long term [10]. Despite the fact that numerous academic papers and the EU itself cite technological barriers as a significant factor influencing the implementation of circular economy strategies, a comprehensive survey of industry professionals identified cultural challenges as the main obstacle to the adoption [13].

Literature also confirms that a lack of clarity and inherent ambiguity in regulations creates room for interpretation, which is one of the greatest challenges for companies dealing with international sustainability legislation. Small and medium-sized enterprises are particularly affected by such policies, as they often rely on policymakers and the government to provide directions [8].

Another challenge faced by many companies is the lack of resources dedicated to innovation management, which is often seen as too costly and time-consuming. Regarding regulatory compliance, many companies expect that the regulatory authorities provide substantial assistance and incentives for innovations during the compliance process. Possible incentives may include preferential treatment in projects, direct financial aid, or funding of collaborative research initiatives [8, 15].

Significant organizational barriers present another challenge. Companies that merely adhere to regulations without exceeding them to embrace the principles of circular economy are not fully aligned with its core values. This often results in a half-hearted implementation, which creates barriers to internal change, necessary to align the company with a more circular strategy. As a result, the implementation is often set up for failure from the outset [3, 10, 13].

The results show that internal resistance and missing financial ressources are the main hurdles for organizations on their transition to circular economy. Studies show that a radical adoption of circular economy principles often provides higher benefits than incremental changes, but at the same time it also has a higher risk of failure. A cultural change within organizations is essential, but also quite difficult to achieve.

Some larger companies face change management challenges by creating an independent innovation team within the company. These teams operate autonomously and report directly to top management. This approach leads to minimal disruptions to the core organization while at the same time enabling the exploration of circular economy strategies. However, such initiatives often require significant financial resources, making them impossible to smaller companies.

Therefore, the challenges of implementing circular economy regulations differ fundamentally with the company size. Small and medium enterprises (SME) often face greater financial and operational limitations, making it difficult to allocate resources to compliance and innovation. The high cost of research and development combined with limited access to finance leads to a greater focus on short-term survival rather than long-term sustainability strategies [27].

8 CONCLUSION

In conclusion, the selected case studies support the hypothesis that sustainability legislation can positively impact innovation, at least regarding the German Circular Economy Act. However, the extent of this impact remains unclear. Industries demonstrating strong innovation in response to circular economy regulations benefit from technological adaptability, access to capital, and established research and development structures. High-tech manufacturing progresses rapidly, leveraging existing know-how to develop new materials and optimise production processes. In contrast, traditional manufacturer and SMEs struggle with high acquisition costs, technological complexity, and regulatory uncertainties that limit their ability to implement sustainable innovations.

Due to the short number of impactful case studies, it would be beneficial for companies to make their efforts more widely known in collaboration with researchers. Therefore, future research should seek to quantify the impact of sustainability legislations on innovation. In addition, future research could explore alternative theoretical models to further analyse the relationship between sustainability legislation and innovation. For example, the Green CMD model provides a framework to assess how environmental regulations drive eco-investments and eco-innovations [28]. Similarly, Bocken et al.'s archetypes of sustainable business models can help explain the cultural and organizational changes required to adopt sustainable approaches [29]. Furthermore, future studies could explore how these findings apply to other countries with different regulatory and economic contexts.

9 REFERENCES

[1] https://www.esgbook.com/wp-content/uploads/2023/07/ESG-Performance-Score_Launch-Press-Release.pdf

[2] Ying, Y. & Jin, S. (2024). Impact of environmental regulation on corporate green technological innovation: the moderating role of corporate governance and environmental information disclosure. *Sustainability, 16*(7), 3006. https://doi.org/10.3390/su16073006

[3] Calisto Friant, M., Vermeulen, W. & Salomone, R. (2021). Analysing European Union circular economy policies: words versus actions. *Sustainable Production and Consumption, 27*, 337-353. https://doi.org/10.1016/j.spc.2020.11.001

[4] Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333-339.

https://doi.org/10.1016/j.jbusres.2019.07.039
[5] Mathis, O., Rose, M., Newig, J. & Bauer, S. (2023). Toward the sustainability state? Conceptualizing national sustainability institutions and their impact on policy-making. *Environmental Policy and Governance, 33*(3), 313-324. https://doi.org/10.1002/eet.2032
[6] Salminen, J. & Rajavuori, M. (2019). Transnational sustainability laws and the regulation of global value chains: comparison and a framework for analysis. *Maastricht Journal of European and Comparative Law, 26*(5), 602-627. https://doi.org/10.1177/1023263X19871025
[7] Almaqtari, F., Elsheikh, T., Hussainey, K. & Al-Bukhrani, M. (2024). Country-level governance and sustainable development goals: implications for firms' sustainability performance. *Studies in Economics and Finance, 41*(3), 684-723. https://doi.org/10.1108/SEF-05-2023-0272
[8] Demirel, P. & Danisman, G. (2019). Eco-innovation and firm growth in the circular economy: evidence from European small- and medium-sized enterprises. *Business Strategy and the Environment, 28*(8), 1608-1618. https://doi.org/10.1002/bse.2336
[9] Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A. & Hekkert, M. (2018). Barriers to the circular economy: evidence from the European Union (EU). *Ecological Economics, 150*, 264-272. https://doi.org/10.1016/j.ecolecon.2018.04.028
[10] Kuhlmann, M., Bening, C. & Hoffmann, V. (2023). How incumbents realize disruptive circular innovation. Overcoming the innovator's dilemma for a circular economy. *Business Strategy and the Environment, 32*(3), 1106-1121. https://doi.org/10.1002/bse.3109
[11] Suchek, N., Fernandes, C., Kraus, S., Filser, M. & Sjögrén, H. (2021). Innovation and the circular economy: a systematic literature review. *Business Strategy and the Environment, 30*(8), 3686-3702. https://doi.org/10.1002/bse.2834
[12] Winans, K., Kendall, A. & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews, 68*, 825-833. https://doi.org/10.1016/j.rser.2016.09.123
[13] Kirchherr, J., Reike, D. & Hekkert, M. (2017). Conceptualizing the circular economy: an analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005
[14] https://eur-lex.europa.eu/EN/legal-content/glossary/circular-economy.html
[15] Cainelli, G., D'Amato, A. & Mazzanti, M. (2020). Resource efficient eco-innovations for a circular economy: evidence from EU firms. *Research Policy, 49*(1), 103827. https://doi.org/10.1016/j.respol.2019.103827
[16] Horbach, J. & Rammer, C. (2020). Circular economy innovations, growth and employment at the firm level: empirical evidence from Germany. *Journal of Industrial Ecology, 24*(3), 615-625. https://doi.org/10.1111/jiec.12977
[17] Ren, Q. & Albrecht, J. (2023). Toward circular economy: the impact of policy instruments on circular economy innovation for European small medium enterprises. *Ecological Economics, 207*, 107761. https://doi.org/10.1016/j.ecolecon.2023.107761
[18] Wilts, H. (2017). Key challenges for transformations towards a circular economy: the status quo in Germany. *International Journal of Waste Resources, 7*(1), 1000262. https://doi.org/10.4172/2252-5211.1000262
[19] Cohen, M. & Tubb, A. (2018). The Impact of Environmental Regulation on Firm and Country Competitiveness: A Meta-analysis of the Porter Hypothesis. *Journal of the Association of Environmental and Resource Economists, 5*(2), 371-399. https://doi.org/10.1086/695613
[20] Boldoczki, S., Thorenz, A. & Tuma, A. (2021). Does increased circularity lead to environmental sustainability? The case of washing machine reuse in Germany. *Journal of Industrial Ecology, 25*(4), 864-876. https://doi.org/10.1111/jiec.13104
[21] https://www.bundesregierung.de/breg-de/schwerpunkte/europa/eu-gesetzgebung-370498
[22] Simoens, M. (2024). Unpacking pathways to a circular economy: a study of packaging innovations in Germany. *Sustainable Production and Consumption, 47*, 267-277. https://doi.org/10.1016/j.spc.2024.04.008.
[23] Cimprich, A., Young, S., Schrijvers, D., Ku, A., Hagelüken, C., Christmann, P., Eggert, R., Habib, K., Hirohata, A., Hurd, A., Lee, M.-H., Peck, D., Petavratzi, E., Tercero Espinoza, L., Wäger, P. & Hool, A. (2023). The role of industrial actors in the circular economy for critical raw materials: a framework with case studies across a range of industries. *Mineral Economics, 36*(2), 301-319. https://doi.org/10.1007/s13563-022-00304-8
[24] Istudor, L.-G. & Suciu, M.-C. (2020). Bioeconomy and circular economy in the European food retail sector. *European Journal of Sustainable Development, 9*(2), 501-511. https://doi.org/10.14207/ejsd.2020.v9n2p501
[25] Barak, M., Ginzburg, T. & Erduran, S. (2024). Nature of engineering. *Science & Education, 33*(3), 679-697. https://doi.org/10.1007/s11191-022-00402-7
[26] Jodlbauer, H., Brunner, M., Bachmann, N., Tripathi, S. & Thürer, M. (2023). Supply Chain Management: A Structured Narrative Review of Current Challenges and Recommendations for Action. *Logistics, 7*(4), Article 70. https://doi.org/10.3390/logistics7040070
[27] Lamoureux, S. M., Movassaghi, H. & Kasiri, N. (2019). The Role of Government Support in SMEs' Adoption of Sustainability. *IEEE Engineering Management Review, 47*(1), 110-114. https://doi.org/10.1109/EMR.2019.2898635
[28] van Leeuwen, G. & Mohnen, P. (2016). Revisiting the Porter hypothesis: an empirical analysis of Green innovation for the Netherlands. *Economics of Innovation and New Technology, 26*(1-2), 63-77. https://doi.org/10.1080/10438599.2016.1202521
[29] Bocken, N. M. P., Short, S. W., Rana, P. & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production, 65*, 42-56. https://doi.org/10.1016/j.jclepro.2013.11.039

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Economics of Polymer Electrolyte Membrane Fuel Cells

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Abstract: Hydrogen is considered a key component of the renewable energy transition for the 21st century, with potential applications using fuel cells in the transportation sector, decentralized heating systems, and energy storage. However, the conversion from fossil fuels to hydrogen implies comprehensive research to address technological and socio-economic challenges, enabling its widespread adoption. This paper discusses the economics of fuel cells. A cost analysis of the polymer electrolyte membrane fuel cells (PEMFC) is performed, and current market data and developments are presented.

Keywords: cost breakdown; economics of fuel cells; market analysis; PEMFC; polymer electrolyte membrane fuel cells

1 INTRODUCTION

One of the fundamental concerns of our time is the accelerating climate change, which is primarily driven by increasing global energy demand and the use of fossil fuels [1]. This underscores the need for renewable and clean alternative energy sources [2]. One solution to these challenges is hydrogen, which serves as an emission-free energy carrier. The fact that hydrogen, with a lower heating value of up to 120 MJ/kg, exhibits an expectedly high energy to mass ratio compared to other fuels shows the enormous potential of this element [3]. As hydrogen is particularly suitable as an energy carrier, its production must be based on renewable energies to ensure sustainability. Producing hydrogen using fossil fuels is observed to offer no advantage over the direct use of fossil fuels; consequently, the production of hydrogen by electrolysis is regarded as the most rational course of action [4].

Hydrogen is considered a key component of the renewable energy transition for the 21st century, with potential applications using fuel cells in the transportation sector, decentralized heating systems, and energy storage. However, the conversion from fossil fuels to hydrogen implies comprehensive research to address technological and socio-economic challenges, enabling its widespread adoption [1, 5].

2 STATE OF THE ART

Fuel cells, which transform the chemical energy stored in fuels directly into electricity through electrochemical processes, are widely recognized as advanced power devices due to their remarkable efficiency and minimal emissions. They are classified based on their electrolyte type into (PEMFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), and alkaline fuel cells (AFC) [6]. From a technical point of view, the PEMFC has advantages of up to 80 % electrical efficiency and low operating temperatures between 60 °C and 85 °C [7]. The operating principle of the PEMFC shown in Fig. 1 is based on the utilization of hydrogen and oxygen to generate electrical energy and oxygen. The splitting of hydrogen at the anode into protons (H+) and electrons (e–) is a central process. The protons, which are positively charged due to the splitting of the hydrogen, pass through a polymer electrolyte membrane (PEM) to the cathode, while the electrons, which are negatively charged due to the splitting of the hydrogen, flow through an external circuit and generate electrical energy; at the cathode, the protons and electrons react with oxygen and produce water.

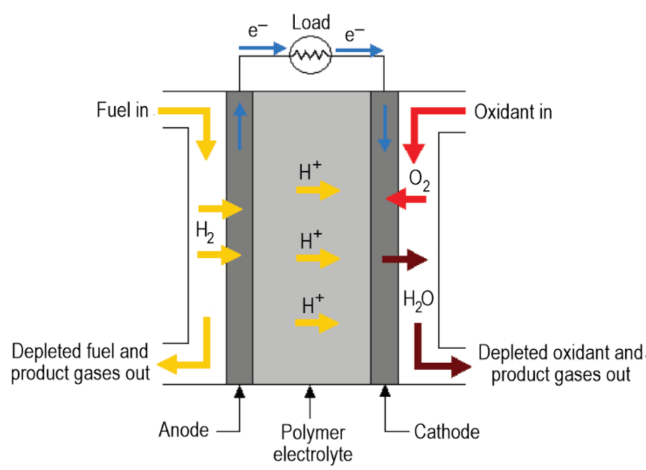

Figure 1 PEMFC schematic operating principle [12]

The PEMFC market volume also shows that the PEMFC is the dominant fuel cell technology today in terms of shipments and power output [8]. Low temperature operation enables rapid start-up and reduces wear on system components, improving overall durability. This approach involves the use of a noble metal catalyst, usually platinum, to facilitate the separation of hydrogen's electrons and protons, which contributes to higher system costs [9]. The PEMFC is considered a potential future type of power source for transportation, stationary and portable applications due to its easy scalability and high-power density. The PEM is used as a conductor for the protons and an electrochemical catalyst to enable reactions at low temperatures [10]. The PEM is coated on both sides with a catalyst layer, which is referred to as catalyst coated membrane (CCM). The CCM is surrounded by two sub gasket layers and is covered on both sides by a gas diffusion layer (GDL). Together this forms the membrane electrode unit (MEA) [11]. Another key component is the bipolar plates (BPP). The MEA is compressed by the BPP that provide a homogeneous supply of reaction gases and is cooling the active area [12, 13]. The individual cells are assembled into a fuel cell stack with the seals, the current collectors, endplates and the gaskets as shown in Fig. 2.

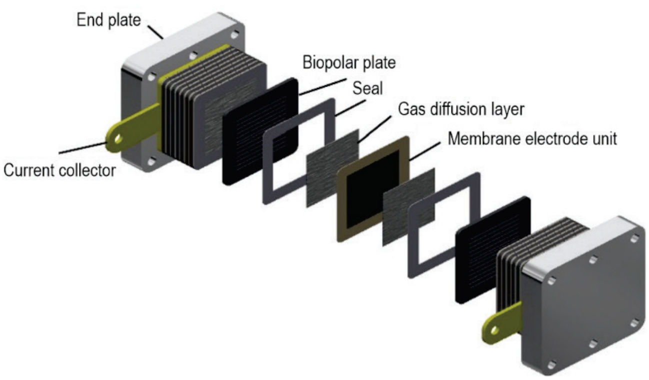

Figure 2 Components of a PEMFC stack [14]

3 METHODOLOGIES

To provide a comprehensive basis for the analysis of the economics of fuel cells, data from several recent relevant studies were used. Firstly, the studies were compared and evaluated based on their methodological approaches to ensure that the underlying data were comparable. For the cost analysis, studies from the Batelle Memorial Institute, Fraunhofer Institute IPT, and RWTH Aachen University were used. Quantitative data from these studies were consolidated into the present results and then presented visually in the form of charts and graphs. These visualizations allow a clear presentation of the relative cost distributions and contribute to a better understanding of the results. To conduct a comprehensive cost analysis, the current material costs associated with the production of PEMFCs were presented. The market analysis was based primarily on ERM's Fuel Cell Industry Review. Three recent market studies on different fuel cell sectors were used to present the prospects.

4 RESULTS
4.1 Cost Breakdown

As part of the Batelle Memorial Institute's 2017 study, a cost analysis was conducted for PEMFC’s with power outputs ranging from 1 kW to 25 kW.

In this study, the costs were analyzed for different numbers of units produced from 100 to 50 000 per year. The cost breakdown focuses on the 10 kW PEMFC and examines the general cost structure on the one hand and the costs related to the components on the other hand.

Assumptions for the cost analysis of a 10-kW fuel cell stack:
- Platinum (Pt) loading: 0,4 mg Pt/cm²
- Power density: 0,54 W/cm²
- Current density: 0,8 A/cm²
- Membrane material: Perfluorinated acids (PFSA), polytetrafluoroethylene reinforced
- Membrane thickness: 0,2 mm
- Number of cells: 106

Fig. 3 shows that as production increases, the cost per unit decreases significantly due to economies of scale. For example, as production volume increases from 100 to 50 000 units per year, the total cost per 10 kW PEMFC stack drops from 7 986 € to 1 490 €, a dramatic reduction of 81,35 %.

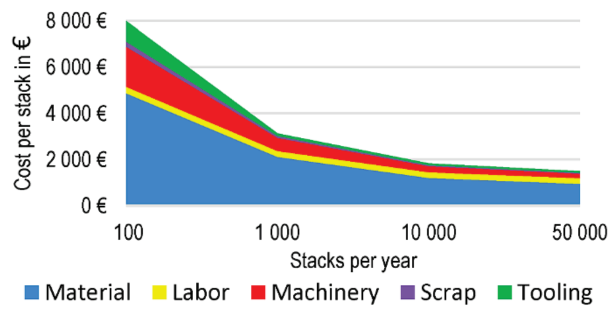

Figure 3 Cost scaling effects for 10 kW PEMFC (adopted from [15])

Fig. 4 shows an example of the cost breakdown for a stack production of 1 000 units per year. Over 67 % of the costs are material costs and over 18 % are machinery costs.

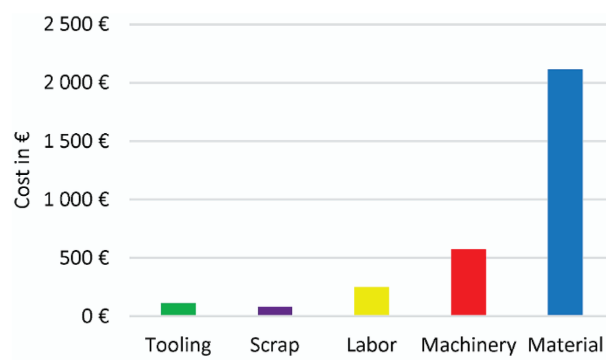

Figure 4 Cost breakdown for 1 000 stacks [15]

In the same study, the specific costs of the components were analyzed for different power outputs and production volumes (Fig. 5). The findings highlight significant economies of scale, as unit costs decrease considerably with higher production volumes. For smaller production volumes of 100 stacks per year, total manufacturing costs amount to 762 €/kW, whereas at 50,000 stacks per year, costs drop to just 142 €/kW. The MEA remains the most expensive component, but its share of total costs decreases as production volume increases. Particularly large cost reductions are observed in assembly, testing, and conditioning, indicating efficiency gains not only in material costs but also in production and quality control. In contrast, the relative cost reduction of the BPP is less pronounced. Generally, scaling effects are more significant for systems with lower production volumes [15].

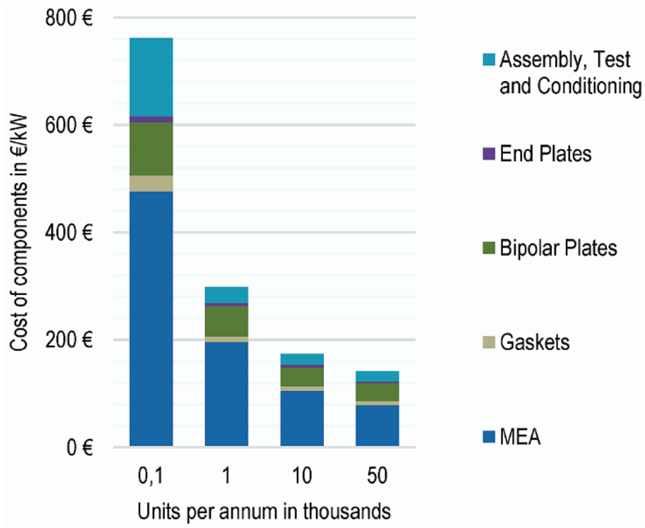

Figure 5 Cost breakdown of components for a 10 kW PEMFC [15]

According to the NOW study conducted by the Fraunhofer Institute for Production Technology IPT, the recurring components of a PEMFC can be qualitatively assessed based on their cost, lifespan, and manufacturing complexity. The end plates, gaskets, and current collectors exhibit relatively low manufacturing complexity and production costs while offering a comparatively long lifespan. In contrast, the MEA, BPP and GDL are identified as the most critical components in PEMFC manufacturing, with the GDL being considered separately from the MEA in this analysis. Among these, the MEA presents the greatest challenges, as it involves a highly intricate manufacturing process, incurs substantial material costs, and has a relatively short operational lifespan. Given these factors, optimizing MEA production techniques and material selection remains a key focus in improving the overall economic viability and durability of PEMFC technology.

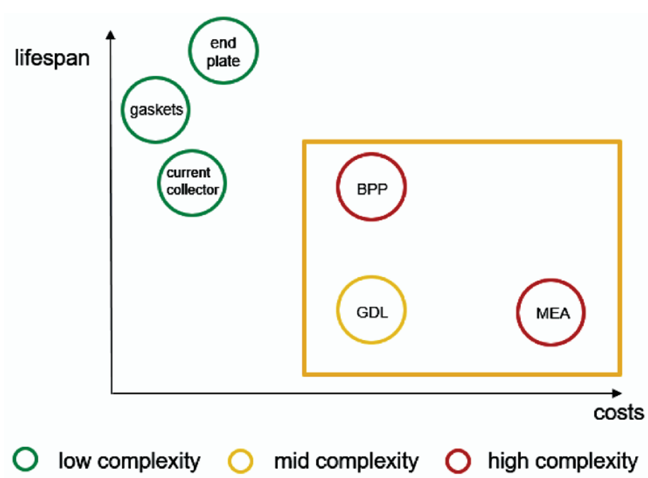

Figure 6 Qualitative evaluation of components according to lifespan, cost, and complexity (adapted from [16])

The material and machine costs for these three components, which are considered significant in the overall cost structure of the study from the Batelle Memorial Institute, are shown below.

Tab. 1 presents the conventional materials used in a PEMFC stack along with their current prices (September 2024). The cost of the catalyst, a key component of the MEA, significantly impacts the overall price. Additionally, there is a notable price difference between metal-based and graphite-based materials for the BPP, leading to a trade-off between cost, durability, and efficiency [11]. To facilitate cost comparisons, membrane prices are given in €/m², while all other materials are listed in €/kg. This approach allows for a clearer assessment of material cost impacts and highlights differences between components, such as the high cost of catalysts or the varying prices of BPP substrates and MEA membranes. Furthermore, the physical properties provided in the table offer valuable insight into the required material quantities and dimensions, which directly influence both the cost structure and the overall fuel cell stack design.

Table 1 Costs of the PEMFC stackstast components [13, 17-25]

Component	Material	Price	Physical properties
MEA Membrane	Nafion NR212 SPEEK-K Aquivion E98-15S	~ 3 306 €/m² ~ 172,95 €/m² ~ 12 800 €/m²	50,8 µm 105 µm 150 µm
MEA Catalyst	Platinum Rhodium	~ 28 790 €/kg ~ 147 740 €/kg	0,2 mg/cm² 0,01 mg/cm²
GDL	Carbon-fiber-based porous paper	~ 7 941 - 13 235 €/kg	0,3 - 0.5 g/cm³
BPP Substrate	Stainless steel Titanium Aluminium Graphit	~ 8,5 - 8,8 €/kg ~ 120 - 170 €/kg ~ 12,3 - 23,3 €/kg ~ 1 €/kg	8 g/cm³ 4,5 g/cm³ 2,7 g/cm³ 1,9 g/cm³
BPP Coating	Gold-based Carbon-based Metal nitrides	> 47 000 €/kg ~ 0,7 €/kg ~ 500 €/kg	19,3 g/cm³ 2,3 g/cm³ 5,2 g/cm³

According to the study by the Batelle Memorial Institute, machine costs represented the second largest cost center in PEMFC production. The following analysis highlights the components with the highest machinery costs.

The report by RWTH Aachen University and VDMA evaluated the machine costs for individual process steps in the production of PEMFC components. Fig. 7 shows the machine costs to produce the CCM, with the highest costs of 1 million € for coating the decals, followed by 0,9 million € for attaching the sub gaskets.

Fig. 8 shows the machine costs to produce the GDL component. With a total cost of €2,8 million, coating and sintering account for the largest share at €1,4 million.

Fig. 9 displays the machine costs for the BBP, with forming and cutting accounting for the largest share at 4,1 million €.

Fig. 10 provides the total machine costs for all production steps and illustrates that the production of the BPP accounts for the largest share of the costs at 8.6 million €. The machine costs to produce the MEA, which includes the production of the CCM, the GDL, and the assembly of the MEA, amount to a total of 8.4 million €. These machinery costs, representing the investments in machines and equipment required for the manufacturing process, result in an overall investment requirement of approximately 17 million € to cover the machine costs to produce all components [26].

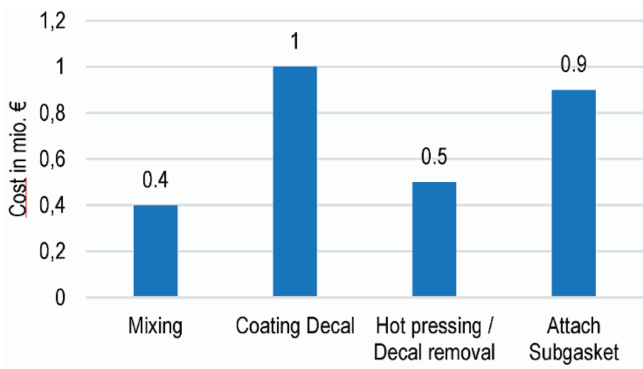

Figure 7 Machinery cost for CCM manufacturing [26]

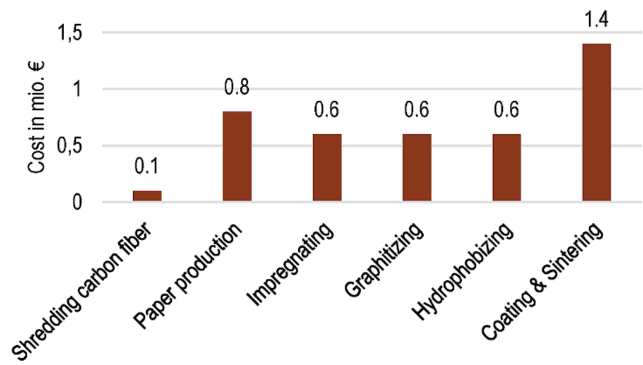

Figure 8 Machinery cost for GDL manufacturing [26]

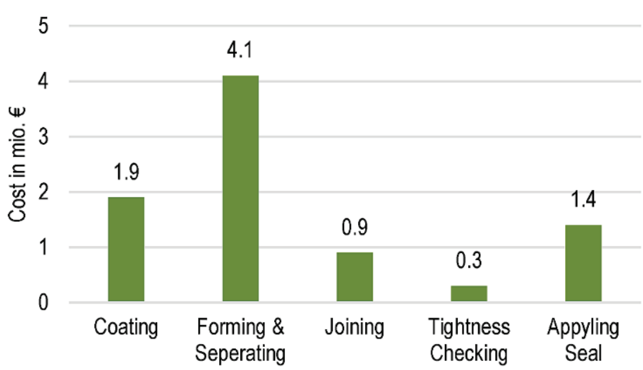

Figure 9 Machinery cost for BPP manufacturing [26]

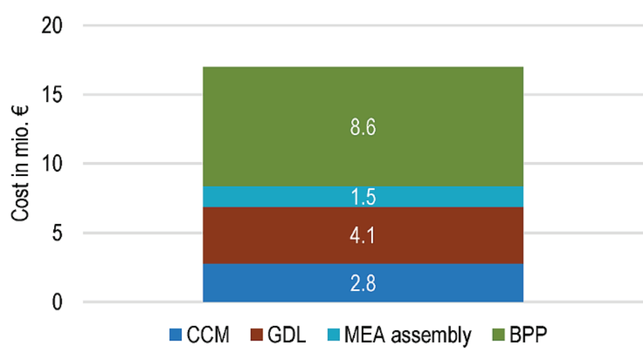

Figure 10 Total machinery cost for the PEMFC [26]

4.2 Market Analysis

The fuel cell market is highly diverse, with PEMFCs leading the sector. In terms of sales, PEMFC technology accounted for the largest share, representing 61 % of all fuel cells sold in 2022, amounting to a total of 89 200 units. SOFCs followed, capturing a 27 % market share as shown in Fig. 11.

With regard to installed capacity, PEMFCs are by far the most dominant. Fig. 11 shows the power output in 2022, which totalled over 2,49 GW. Of this, PEMFCs accounted for approximately 2,15 GW, representing around 86 % of the cumulative installed capacity in gigawatts.

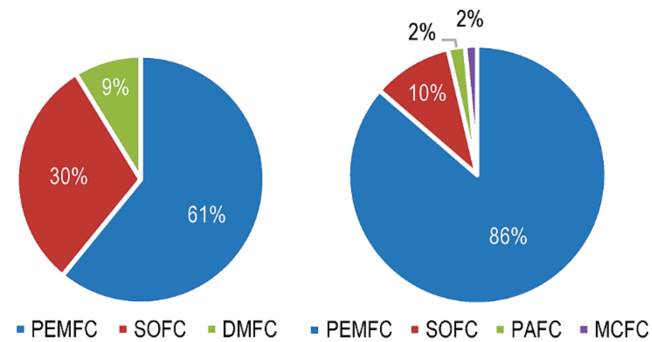

Figure 11 Shipments (left) and power output (right) by FC type [8]

Fuel cells play a crucial role across multiple industries and applications, with their deployment primarily concentrated in three key sectors. Tab. 2 provides an overview of the fuel cell types used and their typical applications within these sectors.

Table 2 Overview fuel cell sectors [6, 8]

	Transport	Stationary	Portable
Typical applications	fuel cell electric vehicles (FCEVs), buses, forklifts and trucks	power and heat generation for uninterruptible supplies in a permanent place	small-scale applications like portable chargers and small auxiliary power units
Fuel cell type	PEMFC	SOFC, PAFC, MCFC, AFC	PEMFC, AFC

In 2022, deliveries in the stationary sector were the most significant at over 57 %, followed by the transport sector, which accounted for just over a third of total shipments. In contrast, most megawatts were generated in the transportation sector (85 %) and 15 % in the stationary sector [8].

Table 3 Overview market analysis of fuel cells [27-29]

	Precedence research	Morder intelligence	Allied market research
Scope of investigation	Fuel cell market	PEMFC market	FCEV market
Investigation period	2024-2034	2024-2029	2022-2032
CAGR	26,2 %	18,4 %	43 %

There are several forecasts that assess the development of economics of fuel cells differently. Tab. 3 shows the different stages of development of the individual markets. The FCEV market has the highest growth potential with an impressive Compound Annual Growth Rate (CAGR) of 43 %, indicating the increasing demand for hydrogen vehicles and the decarbonization of transportation. In summary, the fuel cell market is forecast to record significant growth, although there are considerable differences in the growth rates of the individual market segments. The various segments are developing at different rates, which indicates different degrees of maturity.

The development of FCEV sales is another critical aspect, with significant growth expected in major regions like China, Europe, Japan, South Korea, and the USA. The cost of fuel cell stacks for automotive use is anticipated to decrease significantly, dropping by 84 % from 2006 to 2050 due to advancements in technology and increased production volumes [16, 28].

The prospects for fuel cells are driven by several factors:

1) **Technological Advancements:** Continuous improvements in fuel cell technology will lead to higher efficiency and lower costs [27].
2) **Government Policies:** Supportive policies and incentives for clean energy will boost market adoption [28].
3) **Infrastructure Development:** Investments in hydrogen infrastructure, including production, storage, and distribution, will facilitate the growth of the fuel cell market [29].
4) **Environmental Concerns:** Growing awareness and regulatory measures to reduce carbon emissions will drive the adoption of fuel cells [30].

5 CONCLUSION

The economic analysis presented in this report highlights the critical importance of scaling production, optimizing material and equipment expenditures, and evaluating market expansion potential. Material costs constitute the predominant portion of total stack costs and, while substantial reductions can be achieved through large-scale manufacturing, they remain the principal cost determinant. Among the various stack components, the MEA emerges as a primary cost driver, largely due to the high expenses associated with platinum and rhodium catalysts. The analysis further reveals inherent trade-offs between cost, efficiency, and durability, particularly in the selection of coatings for bipolar plates, where material composition significantly influences overall expenditure. Market projections indicate robust growth within the fuel cell sector, with PEMFCs expected to play a pivotal role in the future energy landscape, driven by ongoing technological advancements and supportive policy frameworks. Future research should focus on alternative catalyst materials to reduce dependency on platinum-group metals, advanced manufacturing techniques for cost-effective mass production, and innovative bipolar plate coatings that enhance both durability and performance while maintaining economic feasibility. Additionally, further analysis of supply chain resilience and policy-driven incentives could provide deeper insights into long-term market viability and investment strategies.

6 REFERENCES

[1] Singla, M. K., Nijhawan, P., & Oberoi, A. S. (2021). Hydrogen fuel and fuel cell technology for cleaner future: a review. *Environmental Science and Pollution Research, 28*(13), 15607-15626. https://doi.org/10.1007/s11356-020-12231-8

[2] Sayed, E., Olabi, A., Alami, A., Radwan, A., Mdallal, A., Rezk, A., & Abdelkareem, M. (2023). Renewable Energy and Energy Storage Systems. *Energies, 16*(3), 1415. https://doi.org/10.3390/en16031415

[3] Paschotta, R. (n. d.). *Wasserstoff*. In *Energie-Lexikon*. Abgerufen am 03. Februar 2025, von https://www.energie-lexikon.info/wasserstoff.html

[4] Agyekum, E. B., Ampah, J. D., Wilberforce, T., Afrane, S., & Nutakor, C. (2022). Research progress, trends, and current state of development on PEMFC—New insights from a bibliometric analysis and characteristics of two decades of research output. *Membranes, 12*(11), 1103. https://doi.org/10.3390/membranes12111103

[5] Ghenai, C., Salameh, T., & Merabet, A. (2020). Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region. *International Journal of Hydrogen Energy, 45*(20), 11460-11470. https://doi.org/10.1016/j.ijhydene.2018.05.110

[6] Wang, Y., Seo, B., Wang, B., Zamel, N., Jiao, K., & Adroher, X. C. (2020). Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. *Energy and AI, 1*, 100014. https://doi.org/10.1016/j.egyai.2020.100014

[7] Alaswad, A., Omran, A., Sodre, J. R., Wilberforce, T., Pignatelli, G., Dassisti, M., Baroutaji, A., & Olabi, A. G. (2021). Technical and commercial challenges of proton-exchange membrane (PEM) fuel cells. *Energies, 14*(1), 144. https://doi.org/10.3390/en14010144

[8] The ERM International Group Limited. (2022). *The fuel cell industry review 2022*. https://www.erm.com/solutions/climate-net-zero/the-fuel-cell-industry-review/

[9] Office of Energy Efficiency & Renewable Energy. (n. d.). *Types of fuel cells: Hydrogen and Fuel Cell Technologies Office*. U. S. Department of Energy. Abgerufen von https://www.energy.gov/eere/fuelcells/types-fuel-cells

[10] Wang, Y., Ruiz Diaz, D. F., Chen, K. S., Wang, Z., & Adroher, X. C. (2020). Materials, technological status, and fundamentals of PEM fuel cells – A review. *Materials Today, 32*, 178–203. https://doi.org/10.1016/j.mattod.2019.06.005

[11] Fraunhofer IPT/WZL der RWTH Aachen. (2022b). *Technologischer Deep-Dive: Die Membran-Elektroden-Einheit der PEM-Brennstoffzelle*. https://www.now-gmbh.de/wp-content/uploads/2022/10/Deep-Dive_MEA.pdf

[12] Debe, M. K. (2012). Electrocatalyst approaches and challenges for automotive fuel cells. *Nature, 486*(7401), 43-51. https://doi.org/10.1038/nature11115

[13] Fraunhofer IPT/WZL der RWTH Aachen. (2022a). *Technologischer Deep-Dive: Die Bipolarplatte der PEM-Brennstoffzelle*. https://www.now-gmbh.de/wp-content/uploads/2022/10/Deep-Dive_Bipolarplatte.pdf

[14] Fra Kühne, P., & Wenske, M. (2024). *Fuel cells: Functionality, types and applications*. https://www.dilico.de/en/brennstoffzellen.php

[15] Battelle Memorial Institute. (2017). *Manufacturing cost analysis of 1, 5, 10, and 25 kW fuel cell systems for primary power and combined heat and power applications.* U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2018/02/f49/fcto_battelle_cost_analysis_mhe_jan2017.pdf

[16] Führen, D., Graw, M., Kröll, L., Ilsemann, J., Robinius, M., Wienert, P., Aretz, M., Janssen, H., Kresting, M., & Müller, C. (2022). *Wertschöpfungskette Brennstoffzelle: Metastudie.* NOW GmbH. https://www.now-gmbh.de/wp-content/uploads/2022/08/NOW_Wertschoepfungskette-Brennstoffzelle.pdf

[17] Chang, S., Ye, J., Zhou, W., Wu, C., Ding, M., Long, Y., Cheng, Y., & Jia, C. (2019). A low-cost SPEEK-K type membrane for neutral aqueous zinc-iron redox flow battery. *Surface and Coatings Technology, 358*, 190-194. https://doi.org/10.1016/j.surfcoat.2018.11.028
[18] MSE Supplies. (n.d.). *Aquivion membrane 20 mm dia (pack of 100)*. MSE Supplies. Abgerufen am 9. September 2024, von https://www.msesupplies.com/products/aquivion-membrane-20-mm-dia-pack-of-100?srsltid=AfmBOopBxnK_tjxpgDxqyqGqbkzD26KV0IuiwoBxgTnYjumVUI7h9it6&variant=39887823011898
[19] Boerse.de. (n.d.). *Platinpreis* [Historische Kurse]. Abgerufen am 9. September 2024, von https://www.boerse.de/historische-kurse/Platinpreis/XC0009665545
[20] Daily Metal Price. (n.d.). *Rhodium price*. Abgerufen am 9. September 2024, von https://www.dailymetalprice.com/rhodium.html
[21] Quintech. (n.d.). *GDL340-2 - Carbon paper*. Abgerufen am 9. September 2024, von https://www.quintech.de/en/produkte/components/gas-distribution-layer/carbon-paper/gdl340-2/
[22] Statista. (n.d.). *Durchschnittlicher Preis für Graphit weltweit*. Abgerufen am 9. September 2024, von https://de.statista.com/statistik/daten/studie/1361213/umfrage/durchschnittlicher-preis-fuer-graphit-weltweit/
[23] Wang, Y., Ruiz Diaz, D. F., Chen, K. S., Wang, Z., & Adroher, X. C. (2020). Materials, technological status, and fundamentals of PEM fuel cells – A review. *Materials Today, 32*, 178-203. https://doi.org/10.1016/j.mattod.2019.06.005
[24] Frontis Energy. (n.d.). *Nafion™ NR212 Membran*. Frontis Energy. Abgerufen am 27. Februar 2025, von https://shop.frontis-energy.com/nafion-tm-nr212-membran
[25] Pérez, G., Díaz-Sainz, G., Gomez-Coma, L., Alvarez-Miguel, L., Garnier, A., Cabon, N., Ortiz, A., Gloaguen, F., & Ortiz, I. (2022). Rhodium-based cathodes with ultra-low metal loading to increase the sustainability in the hydrogen evolution reaction. *Journal of Environmental Chemical Engineering, 10*(4), 107682. https://doi.org/10.1016/j.jece.2022.107682
[26] Heimes, H. H., Kehrer, M. M., Hagedorn, S., Hausmann, J., Krieger, G., & Müller, J. (2022). *Produktion von Brennstoffzellenkomponenten* (2. Aufl.). PEM der RWTH Aachen und VDMA AG Brennstoffzellen. ISBN 978-3-947920-25-9.
[27] Precedence Research. (2024). *Fuel cell market*. Abgerufen am 9. September 2024, von https://www.precedenceresearch.com/fuel-cell-market
[28] Mordor Intelligence. (2024). *Polymer electrolyte membrane fuel cell market size & share analysis – Growth trends & forecasts (2024–2029).* Abgerufen am 9. September 2024, von https://www.mordorintelligence.com/industry-reports/global-polymer-electrolyte-membrane-pem-fuel-cells-market-industry
[29] Allied Market Research. (2023). *Hydrogen vehicle market – 2032.* Abgerufen am 9. September 2024, von https://www.alliedmarketresearch.com/hydrogen-fuel-cell-vehicle-market
[30] UNFCCC. (2018). *The Paris Agreement – Publication.* Abgerufen am 9. September 2024, von https://unfccc.int/documents/184656

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Artificial Intelligence in Knowledge Management: Overview and Selection of Software for Automotive Reporting

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Abstract: Knowledge Management is essential for modern organizations, enabling the systematic capture, organization, and sharing of knowledge to enhance decision-making and innovation. Traditional Knowledge Management tools, focused on document storage and retrieval, struggle with unstructured data and collaboration, necessitating advanced technological solutions, particularly those incorporating Artificial Intelligence. - Artificial Intelligence-driven Knowledge Management systems revolutionize data handling through automation, and real-time insights. This is particularly valuable in data-intensive industries like automotive, finance, and healthcare. In the automotive sector, annual reports provide critical insights but are complex and time-consuming to analyze and are a complex example and therefore a good test case. Annual reports of 5 major automotive companies BMW, Volkswagen group, Toyota Motors, General Motors and Tesla were selected as the testing dataset. Artificial Intelligence tools, using natural language processing and machine learning, streamline data extraction. - Despite their benefits, organizations face challenges in selecting the right Artificial Intelligence-driven Knowledge Management software due to a lack of standardized evaluation frameworks. This research applies a systematic methodology for assessing such software, considering usability, adaptability, cost-effectiveness, and data privacy compliance, specifically tailored to automotive reporting and gives recommendation for software tools.

Keywords: Artificial Intelligence; Automotive Reporting; Knowledge Management; Software Assessment; Technology Assessment

1 INTRODUCTION

1.1 Motivation, Objectives & Research Questions

Knowledge management (KM) enhances decision-making and innovation by systematically capturing, organizing, and sharing organizational knowledge. Traditional KM tools struggle with unstructured data and collaboration, necessitating AI-driven solutions. AI significantly enhance productivity, particularly in data-heavy industries like automotive, finance, and healthcare [1]. However, a lack of standardized evaluation frameworks hinders their optimal use [2]. Annual reports are crucial for financial and strategic transparency, especially in the automotive sector, where they guide decision-making and track industry trends and are a complex example and therefore a good test case [3]. Annual reports of 5 major automotive companies BMW, Volkswagen group, Toyota Motors, General Motors and Tesla were selected as the testing dataset. These reports contain extensive data, making manual analysis time-consuming. AI automates content summarization and trend identification, improving efficiency and research quality [4].

This paper gives an overview and selects AI knowledge management software for automative reporting with a systematic methodology based on existing software selection frameworks [5]. The structured approach assesses usability, adaptability, cost-effectiveness, and data privacy compliance, providing insights into optimal tools for analyzing automotive reports and supporting future research and gives a recommendation for tools. This research is going to answer the following research questions

1) What AI driven knowledge management software tools are on the market?
2) How do usability, adaptability, cost-effectiveness, and data privacy compliance impact the selection of AI-driven KM platforms for automotive reporting?
3) What is the most suitable AI-driven Knowledge management software tool for analyzing automotive reports based on the developed evaluation methodology?

1.2 Core Feature & Use Cases of AI Knowledge Management

AI-driven knowledge management (KM) platforms integrate advanced technologies to enhance operations, decision-making, and data insights, playing a crucial role in the automotive sector. Natural Language Processing (NLP) enhances machine understanding of human language using transformer-based models like BERT and GPT, improving semantic search, summarization, and translation [6], [7].

Automated Data Extraction converts unstructured data into structured formats using Named Entity Recognition (NER) and Optical Character Recognition (OCR), reducing human intervention. Predictive Analytics employs machine learning techniques to forecast trends and detect anomalies, aiding risk management and market analysis. Chatbots and Virtual Assistants leverage NLP and frameworks like Rasa to improve knowledge retrieval, streamline onboarding, and support automated help desks [8]. Machine Learning (ML) enables KM platforms to evolve, supporting personalized recommendations, document categorization, and knowledge clustering. Knowledge Graphs use graph databases like Neo4j to map relationships, enhancing search and information discovery. Image and Video Recognition employs convolutional neural networks (CNNs) for multimedia analysis, expanding KM capabilities in visual data-intensive industries [9].

In research and development (R&D), AI-powered platforms like Notion and Guru facilitate knowledge sharing, reducing redundancies and accelerating innovation. AI models like ChatGPT analyze and summarize complex technical documents, improving information retrieval [9]. Predictive analytics aids in forecasting trends and regulatory changes, ensuring strategic alignment [6]. Product lifecycle management (PLM) benefits from AI-driven KM, tracking information from design to maintenance. Predictive analytics anticipates technical issues and identifies enhancement opportunities [9]. Coda integrates with IoT sensors, offering real-time insights into malfunctions, optimizing maintenance and vehicle design [6].

Supply chain optimization relies on AI-driven KM for demand forecasting, risk identification, and procurement decisions. AI analyzes supply chain data, predicts fluctuations, and tracks supplier reliability. Tools like Notion and Guru provide real-time insights into market conditions, minimizing inefficiencies [8]. AI-driven KM automates financial reporting by extracting and summarizing key data from annual reports, reducing manual analysis. NLP scans Management Discussion and Analysis (MD&A) sections for qualitative insights on corporate strategy and market positioning. AI tools track trends across reports, offering insights into financial performance [6].

Strategic risk management benefits from AI-powered KM tools that monitor regulatory changes, supply chain disruptions, and competition. Predictive analytics helps platforms like Guru assess market trends and identify risks before they materialize. AI-driven systems assist compliance teams in tracking regulations across markets, providing actionable compliance insights [9]. These AI-driven KM applications enhance efficiency, decision-making, and risk mitigation, driving innovation and sustainability in the automotive industry [6], [8].

In this context analyzing Automative Reporting with Knowledge Management software as a complex example becomes more and more important in practice and as use case for research.

2 METHOD & APPROACH

To evaluate and compare AI-driven Knowledge Management (KM) tools for analyzing automotive industry reports, a systematic approach was designed. The methodology involves defining the problem, systematically searching for tools, filtering them based on specific criteria, evaluating their capabilities using a weighted decision matrix, and conducting real-world testing for two selected software (see figure 1).

Market research begins with defining the scope of the software search, selecting tools based on KM functionalities, AI-powered features, availability as free/open-source, and positive user ratings. A systematic Google search using predefined keywords ("Knowledge Management Software", "AI-powered Knowledge Management Tools," "Free KM Software", "Top-rated Knowledge Management Platforms") helps document frequently mentioned tools, which is complemented by AI-assisted searches using ChatGPT to retrieve lists of KM software and key attributes. Identifying recurring tools from both sources helps create a refined shortlist. Filtering and screening involve defining criteria related to data processing, search functionality, ease of use, and pricing. Verification methods include cross-checking features via comparison websites, vendor descriptions, and hands-on testing. The elimination process sequentially removes tools failing key requirements, narrowing the selection to the top five for further evaluation (see chapter 3.1).

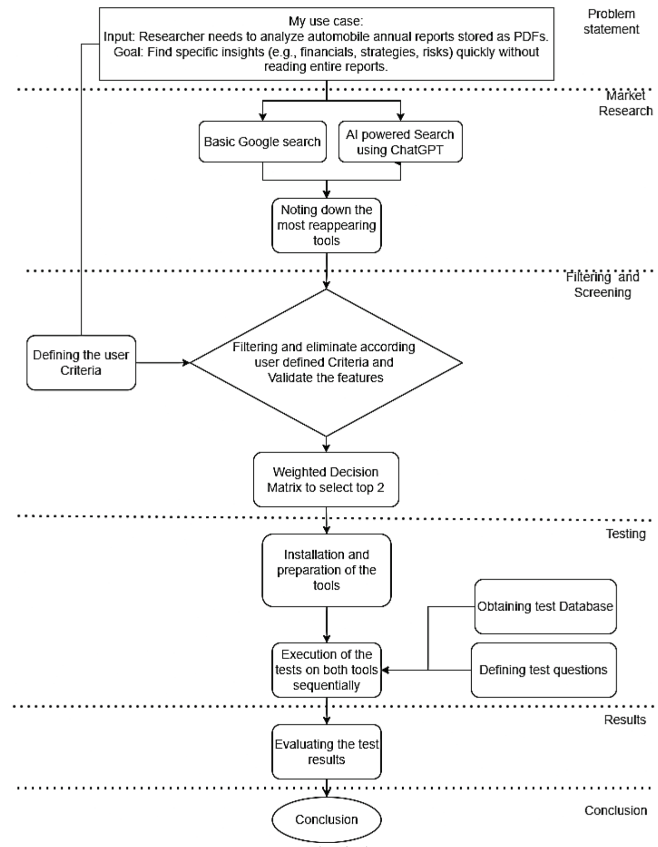

Figure 1 Methodology for Software tool selection

The decision matrix evaluates software using four major criteria: robust AI capabilities (NLP quality, summarization accuracy), ease of use (speed, document handling, offline usability), data privacy (local storage, cloud access permissions), and pricing (free or student-friendly plans). Each tool is rated on a 1–5 scale, weighted (AI Capabilities 50%, Ease of Use 40%, Data Privacy 10%, Pricing 30%), and assessed using a weighted decision matrix to determine the top two tools for real-world testing. Selection of criteria and weightage was done in line with research in this field [5, 25-28] (see chapter 3.2).

The testing phase includes installation, data collection from five automotive companies, and structured queries to assess tool performance in extracting, calculating, and analyzing data. Execution involves document upload assessment, AI-driven query execution, and multi-section analysis. Observation metrics include accuracy (data correctness verification), responsiveness (query processing speed), functionality (document handling efficiency), and limitations/errors (missing features, inaccuracies, usability concerns) (see chapter 3.3).

This structured methodology ensures a thorough, scientific evaluation of AI-powered KM tools for academic and industry research applications.

3 RESULTS: SELECTION OF ARTIFICIAL INTELLIGENCE-DRIVEN SOFTWARE FOR AUTOMOTIVE REPORTING

3.1 Market Research & Filtering

Market research was done to evaluate the most prominent "AI-Driven Knowledge Management Tools. The core of the research was done with a systematic Google search and ChatGPT search with predefined keywords: "Knowledge Management Software", "AI-powered Knowledge Management Tools", "Free KM Software," "Top-rated Knowledge Management Platforms." This search was supported by a literature search of scientific articles about theses software tool in knowledge management. The following software tools could be identified: Confluence, Notion, Guru, Microsoft OneNote, ChatGPT, Coda, Evernote, Obsidian, Glean, Roam Research.

Tab. 1 provides an overview of the software tools identified for further research and corresponding scientific articles.

Table 1 Selected Software Tools for AI-driven Knowledge Management [10-24]

Tool	Description	Scientific Papers (Harvard)
Notion	Highlighted for its seamless integration of databases and task management.	Smith (2020), Brown and Green (2021), Davis (2019)
Guru	Praised for its in-context AI suggestions and automated content improvement.	Johnson (2018), Lee and Kim (2019), Patel (2020)
ChatGPT	Emphasized for generating natural language responses and document summarization.	Zhou et al. (2023), Zhang et al. (2023), Gao et al. (2024)
Coda	Noted for its extensive customization and AI pack integrations.	Newman (2022), Finnegan (2022), McCracken (2018)
Evernote	Lauded for its cross-platform usability and organizational features.	Thompson (2017), Martin and Clark (2018), Roberts (2019)

Confluence, Microsoft OneNote, Obsidian, Glean, Roam Research have been excluded:

Obsidian lacks native support for analyzing text within PDF documents, which limits its applicability for comprehensive document processing. The software requires additional plugins to enable AI-based responses and does not natively support natural language queries. While available for free, optimal utilization necessitates technical configuration, making it less accessible for non-technical users.

Glean is primarily designed for large organizations and does not offer a downloadable standard version for individual users. The software provides personalized solutions rather than a universally accessible standard version, limiting its usability for general knowledge management applications.

Confluence is structured primarily for document sharing rather than in-depth document analysis. It relies on integration with external tools for AI-driven search capabilities and does not return strictly input-based responses. Advanced features are locked behind paid versions, and offline functionality remains limited.

Microsoft OneNote excels in notetaking but lacks advanced text analysis functionalities. It does not incorporate a built-in AI-driven natural language response system. The software does not provide fully functional offline knowledge management capabilities for processing multiple documents simultaneously.

Roam Research is optimized for creating a network of interconnected ideas rather than for processing large sets of documents. The platform does not meet the requirement for input-specific search functionalities. A paid subscription is necessary to access the software, and its user interface presents challenges for non-technical users due to limited ease-of-use features.

3.2 Weighted Decision Matrix to Select Top 2 Software

When selecting the top software platforms for AI-driven knowledge management in the automotive industry, evaluation criteria were weighted based on relevance to the problem statement [25-27]. **Robust AI (40%)** was prioritized as the platform's success depends on AI's ability to process technical and financial language, generate accurate summaries, and adapt to various document formats. **Ease of use (30%)** ranked second due to its impact on adoption and efficiency, ensuring users can focus on insights rather than usability challenges. **Pricing (20%**) was considered important but secondary to AI performance and usability, as long-term benefits outweigh initial costs. Free trials and educational discounts mitigate financial concerns. **Data privacy (10%**) was least weighted since reports analyzed are publicly available, and most platforms already follow strict privacy standards. However, intrusive policies could hinder adoption.

Performing the Weighted Decision Matrix involves evaluating the tools based on the above criteria and assigning scores from 1 to 5 justified by their respective strengths and limitations.

For **Robust AI**, Notion demonstrates strong AI-driven capabilities, including an AI-powered search bar and natural language summarization, though it lacks advanced NLP features like complex calculations and translation, scoring 4. Evernote has powerful OCR functionality but lacks AI search without plugins, scoring 2. Coda excels in summarizing large documents and extracting insights but struggles with comparing multiple sources, scoring 3. ChatGPT leads with its advanced natural language processing, making it the benchmark for AI-driven capabilities, scoring 5. Guru provides AI-driven content suggestions but lacks conversational AI depth, scoring 3.

For **Ease of Use**, Notion has an intuitive interface and automatic PDF-to-text conversion, though the latter is slow, scoring 4. Evernote is known for its straightforward design and offline access, scoring 5. ChatGPT is best for conversational tasks, though document-based workflows require structured prompts, scoring 4. Coda offers customization but requires technical expertise, scoring 2. Guru simplifies knowledge management but is less flexible compared to Notion, prioritizing pre-curated knowledge retrieval over open-ended content creation, scoring 3.

For **Data Privacy**, Notion ensures security with local storage options and encryption, scoring 5. Evernote follows with local storage support, scoring 4. Coda relies on online synchronization and requires an internet connection, though it offers restricted data-sharing options, scoring 2. ChatGPT is cloud-based, which may raise concerns for sensitive data, scoring 2. Guru requires access to external drives and offers no offline functionality, making it less suitable for privacy-conscious users, scoring 1.

For **Pricing**, ChatGPT offers a free version with robust features, requiring a Plus membership for unlimited prompts, scoring 4. Notion provides a student version with sufficient features, though advanced AI functionalities require subscriptions, scoring 4. Evernote has a limited free plan with premium options unlocking more capabilities but still lacking AI, scoring 2. Coda's free version is sufficient for individual users, scoring 5. Guru has limited features in the free version but better pricing for enterprise use, scoring 3.

This analysis highlights the strengths and trade-offs of each tool, allowing for an informed decision based on specific needs and priorities. The summary can be found in Fig. 2. The evaluation matrix revealed that ChatGPT (4.2) and Notion (4.1) scored highest among the tools analyzed, primarily due to their robust AI capabilities and ease of use.

		Notion		Evernote		Coda		Chat GPT		Guru	
Criteria	Weightage (%)	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Robust AI	40	4	1,6	2	0,8	3	1,2	5	2	3	1,2
Ease of use	30	5	1,5	5	1,5	2	0,6	3	0,9	2	0,6
Pricing	20	4	0,8	2	0,4	5	1	2	0,4	3	0,6
Data privacy	10	3	0,3	2	0,2	3	0,3	4	0,4	3	0,3
	Summation		4,1		3,1		3,6		4,2		2,8

Figure 2 Weighted Decision Matrix for AI Knowledge Management Software

3.3 Detailed Software Testing

The initial phase of the preparation process involved the installation and configuration of the necessary software tools to facilitate AI-driven analysis. Two primary tools were selected: ChatGPT and Notion. A ChatGPT Plus subscription was activated to enable access to GPT-4, providing advanced AI-driven analytical capabilities. The platform was accessed via a web-based interface to ensure seamless usability and integration with other research tools. The Notion application was downloaded and installed in a desktop environment. A student subscription was utilized to access additional AI-assisted features and enhanced operational limits, thereby supporting structured data organization and collaboration. A structured set of evaluation questions was formulated to assess the efficacy of the selected tools in analyzing annual reports within the automotive industry. These questions were designed to capture key dimensions of corporate analysis and were categorized into three fundamental themes:

- financial performance
- investment areas, and
- strategic insights.

Financial performance questions focused on revenue trends, profit margins, cost structures, and liquidity assessments. Investment area inquiries were directed at capital allocation, research and development expenditures, and innovation-driven initiatives. Strategic insights encompassed the analysis of corporate strategies, market positioning, competitive advantages, and sustainability measures.

The selection of these themes ensures a comprehensive evaluation of AI-driven tools' ability to extract, synthesize, and interpret complex financial and strategic data. Tab. 2 summarizes the questions, their difficulty, reason/importance, the challenge for AI and a potential time saving in min compared to a manual execution.

Table 2 Overview of Questions and their Impact on testing the tools

Question	Difficulty	Reason	Challenge for AI	Time Saving in min
Earnings Per Share	Basic	Key profitability metric; widely reported	Avoid extracting diluted/adjusted EPS; locating in charts, tables, or text	5–10
Return on Equity	Medium	Measures shareholder returns	Extracting net income, equity from different sections; calculating average equity	10–15
Return on Assets	Medium	Assesses asset usage efficiency	Finding net income and total assets; identifying terms like "net profit" or "resources"	10–20
Debt-to-Equity Ratio	Medium	Indicates financial leverage	Separating short/long-term liabilities; extracting equity; calculating ratio accurately	15–25
R&D	Medium	Tracks innovation investments	Finding R&D under operating expenses; identifying narrative mentions	20–30
Sustainability Initiatives	Advanced	Shows ESG commitment	Extracting scattered data; synthesizing qualitative info into measurable insights	30–45
Top Risks	Advanced	Highlights major risks and mitigation	Summarizing dense narratives; separating company risks from industry trends	20–40
Future Products	Advanced	Outlines growth via new products	Extracting from MD&A/CEO letter; separating confirmed and speculative launches	20–30

Annual reports of 5 major automotive companies BMW, Volkswagen group, Toyota Motors, General Motors and

Tesla were selected as the testing dataset. These companies were selected considering the different regions of the worlds, hence different styles of reporting creating a very varied dataset. These reports were used in raw pdf file formats.

The summary of the results is displayed in Tabs. 3 & 4.

Table 3 First part of testing results

Aspect	Chat GPT	Notion
Data Retrieval	Excels in retrieving unstructured data directly from reports, even when spread across multiple sections. However, struggles with tables	Highly effective in retrieving information from well-organized, pre-structured databases.
Summari-zation	Capable of synthesizing dense, complex narratives into concise, meaningful summaries.	Provides summarization features for structured text, but lacks depth for unstructured narratives.
Quantitative Calculation Proficiency Overall	Accuracy (35%) No answer rate (10%) Alternate Answers Rate (45%) performance 80/100	Accuracy (25%) No answer rate (56.25%) Alternate Answers Rate (0%) performance 43.5/100
Qualitative Analysis	Strong in extracting insights, identifying themes, and synthesizing qualitative data into actionable insights. But tries hard to structure the answer and fails to list all required objectives in answers.	Theanswers provided are less paraphrased and relies on returned descriptive answers in more sentences. Delivers more accurately when listing objective answers.
Flexibility	Adapts to diverse document formats and layouts without requiring preprocessing.	Works best when data is pre-organized; struggles with unconventional document formats.
Knowledge Retention	Lacks a persistent memory of previous interactions or documents beyond a single session.	Retains all information in a structured database, enabling long term storage and retrieval.

This study compares ChatGPT and Notion in terms of data retrieval, summarization, quantitative accuracy, qualitative analysis, flexibility, search capabilities, document management, scalability, and adaptability. ChatGPT excels in retrieving unstructured data, synthesizing complex narratives, and handling natural language queries, making it ideal for ad-hoc research tasks. It has higher quantitative accuracy (35%) and a lower no-answer rate (10%) compared to Notion. However, it lacks memory retention, document storage, and structured workflow integration. Notion, on the other hand, is highly effective in managing structured databases, organizing long-term projects, and providing a visually rich interface for document categorization. It ensures better knowledge retention and customization but struggles with unstructured data and unconventional document formats. While ChatGPT is more intuitive and ready-to-use, Notion requires setup and familiarization. Overall, ChatGPT performs better for immediate insights and qualitative synthesis, whereas Notion is more suitable for structured data organization and long-term project management.

Table 4 Second part of testing results

Aspect	Chat GPT	Notion
Search Capabilities	Handles natural language queries effectively, offering quick and accurate responses.	Search functionality relies on database tags and structured keywords for best results.
User Interface	Minimalistic, conversational interface ideal for quick, ad-hoc tasks.	Comprehensive and visually rich interface for organizing tasks, notes, and databases.
Ease of Use	Intuitive and ready-to-use without much setup; minimal learning curve for new users.	Requires initial setup and familiarization, especially for structuring data effectively.
Document Management	Does not allow storing or organizing documents directly; focuses on interactive processing.	Offers robust document management, categorization, and linking capabilities for long-term projects.
Scalability	Handles one-off queries efficiently but lacks tools for large-scale project management.	Excellent for managing large volumes of documents, databases, and tasks over extended periods.
Customi-zation	Limited customization options for workflow integration.	Highly customizable with templates, tags, and relational databases to suit specific workflows.
Security and Privacy	Relies on cloud-based interactions, potentially raising concerns for sensitive data.	Offers more control over data privacy when hosted in private workspaces or secure environments.
Adaptability to Use Case	Well-suited for ad-hoc research tasks and in-depth analysis requiring immediate insights.	Designed for long-term projects requiring systematic organization, structured workflows, and tracking.
Learning Curve	Minimal; easy for users to start without prior experience.	Moderate; requires time to set up databases and workflows effectively.

4 CONCLUSION

This paper successfully applied a systematic methodology for selecting the most suitable software tools for analyzing complex documents, specifically in the context of annual reports in the automotive industry. Annual reports of 5 major automotive companies BMW, Volkswagen group, Toyota Motors, General Motors and Tesla were selected as the testing dataset. These companies were selected considering the different regions of the worlds, hence different styles of reporting creating a very varied dataset. Annual reports are complex and therefore a good test case. By integrating established evaluation frameworks and decision matrices, the proposed approach ensures transparency and reliability in software selection, aligning tools with specific application needs.

But this method depends heavily on the chosen context, user needs, and how criteria are weighted, so minor adjustments can change which software rank highest. Because search engine results and user ratings can vary over time, some software or features may appear or disappear. Additionally, AI capabilities differ with updates or data context, making it hard to generalize findings. Lastly, testing only two software limits the scope of this comparison. Despite these issues, the approach still offers a clear, step-by-step way to justify and compare AI-driven Knowledge Management software.

The evaluation of AI-powered Knowledge Management (KM) software, particularly ChatGPT Plus and Notion, highlighted the strengths and limitations of each tool. ChatGPT Plus excels in processing unstructured data, generating concise summaries, and extracting qualitative insights, making it particularly effective for in-depth, one-time research tasks. On the other hand, Notion provides a structured, collaborative environment, ideal for long-term document management and knowledge organization. While neither tool fully meets all knowledge management needs, their combined capabilities demonstrate the importance of selecting software based on task-specific requirements rather than seeking a one-size-fits-all solution.

Furthermore, the rapid advancements in AI-driven KM tools, including natural language processing, intelligent document parsing, and contextual recommendations, underscore their transformative potential in handling complex, data-heavy reports. The study also emphasized the necessity of adaptable tools, given the diverse reporting styles observed in the automotive sector. AI-powered solutions bridge these gaps by streamlining data extraction, enabling efficient analysis, and reducing cognitive overload for researchers.

Ultimately, this research provides valuable insights into the evolving role of AI in knowledge management, reinforcing the need for strategic software selection in corporate reporting and beyond. The findings offer practical guidance for professionals navigating the complexities of large-scale document analysis, demonstrating how AI-driven Knowledge Management (KM) software can enhance efficiency, decision-making, and research effectiveness.

5 REFERENCES

[1] Deloitte. (2021). *The future of knowledge management with AI*. Deloitte Insights. Retrieved from https://www2.deloitte.com

[2] Forrester. (2023). *Optimizing AI-driven knowledge management platforms*. Forrester Research. Retrieved from https://go.forrester.com/research

[3] German Economic Institute. (2021). *Automotive industry and economic growth*. Köln. Retrieved from https://www.iwkoeln.de

[4] Accenture. (2023). *Enhancing AI adoption in knowledge management*. Accenture Strategy Report. Retrieved from https://www.accenture.com

[5] International Organization for Standardization (ISO/IEC 25010:2011). (2011). *Systems and software engineering—System and software quality requirements and evaluation (SQuaRE)*. Geneva, Switzerland: ISO. Retrieved from https://www.iso.org/standard/35733.html

[6] Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A. N., Kaiser, Ł., & Polosukhin, I. (2017). Attention is all you need. *Advances in Neural Information Processing Systems, 30*, 5998-6008.

[7] Devlin, J., Chang, M. W., Lee, K., & Toutanova, K. (2019). BERT: Pre-training of deep bidirectional transformers for language understanding. *Proceedings of NAACL-HLT 2019*, 4171-4186.

[8] Taherdoost, H., & Madanchian, M. (2023). The impact of AI-powered chatbots on knowledge management systems. *Journal of Artificial Intelligence Research, 45*(2), 112-129.

[9] Mašić, Z., Gudelj, A., & Stanković, R. (2017). The role of knowledge graphs in AI-driven knowledge management. *International Journal of Knowledge Engineering, 13*(1), 67-82.

[10] Smith, J. (2020). Enhancing team collaboration with Notion: A case study. *Journal of Productivity, 15*(3), 45-58.

[11] Brown, L., & Green, K. (2021). Implementing Notion in educational settings. *Educational Technology Research, 22*(1), 78-90.

[12] Davis, M. (2019). Notion as a tool for project management. *International Journal of Project Management, 33*(2), 123-130.

[13] Johnson, P. (2018). Leveraging Guru for knowledge management in tech companies. *Tech Innovations Journal, 10*(4), 67-75.

[14] Lee, S., & Kim, H. (2019). AI-driven knowledge bases: The case of Guru. *Journal of Information Systems, 28*(3), 99-110.

[15] Patel, R. (2020). Improving customer support with Guru's AI capabilities. *Customer Service Quarterly, 12*(2), 45-53.

[16] Zhou, Y., Ringeval, F., & Portet, F. (2023). Can GPT models follow human summarization guidelines? Evaluating ChatGPT and GPT-4 for dialogue summarization. *arXiv preprint*.

[17] Zhang, H., Liu, X., & Zhang, J. (2023). SummIt: Iterative text summarization via ChatGPT. *arXiv preprint*. https://doi.org/10.18653/v1/2023.findings-emnlp.714

[18] Gao, J., Cao, Z., Huang, S., Qin, L., & Ai, C. (2024). Guiding ChatGPT to generate salient domain summaries. *arXiv preprint*. https://doi.org/10.1109/IJCNN60899.2024.10650616

[19] Newman, J. (2022). Coda's new features take on Microsoft Word and Google Docs. *Tech Review Journal, 12*(2), 123-130.

[20] Finnegan, M. (2022). Coda and Notion turn up the heat on Microsoft Office. *Journal of Productivity Tools, 17*(1), 56-70.

[21] McCracken, H. (2018). To turn docs into apps, Coda had to rethink productivity from scratch. *Innovative Tech Review, 9*(3), 45-58.

[22] Thompson, G. (2017). Evernote in academic research: A comprehensive review. *Journal of Academic Librarianship, 23*(4), 123-130.

[23] Martin, A., & Clark, D. (2018). Organizing personal information with Evernote. *Personal Information Management Journal, 11*(2), 56-64.

[24] Roberts, K. (2019). Evernote as a tool for writers: Benefits and drawbacks. *Writing Tools Review, 5*(1), 22-29.

[25] Bitrix24. (n.d.). *Bitrix24: Collaboration, project management & CRM*. Retrieved from https://www.bitrix24.com

[26] Triantaphyllou, E. (2000). *Multi-criteria decision making: A comparative study*. Dordrecht: Kluwer Academic Publishers. https://doi.org/10.1007/978-1-4757-3157-6

[27] Fishburn, P. C. (1967). Methods of estimating additive utilities. *Management Science, 13*(7), 435-453. https://doi.org/10.1287/mnsc.13.7.435

[28] Institute of Electrical and Electronics Engineers (IEEE). (2014). *IEEE standard for system and software verification and validation (IEEE Std 1012-2012)*. New York.

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The Concept of Integrating Interactive Safety Signs into In-Plant Traffic Flow Optimization and Safety Management

Wiktoria Czernecka*, Marcin Butlewski

Abstract: Modern manufacturing companies are characterized by complex internal traffic processes, both pedestrians and forklifts. This results from frequently changing machine locations and thus internal routes, but also from specific production needs, e.g. in the context of customer requirements. Such dynamically developing processes cause problems with ensuring the safety of employees who must move particularly carefully in the production halls. The answer to these problems may be interactive safety signs, which increase employees' attention to dangers, but require a lot of resources for their correct installation. This article presents the concept of implementing interactive signs on the example of a selected production hall. Based on its implementation, a discussion on the required time and cost resources for their installation is also presented in comparison with the benefits and barriers to this implementation.

Keywords: interactive safety signs; occupational health and safety; safety management

1 INTRODUCTION

Nowadays, safety in the workplace is becoming crucial, especially in industrial environments such as production halls. These are places where complex technological processes, intensive machine work and a large number of employees create potential hazards. Therefore, it is so important that every aspect of work organization is well thought out and complies with applicable safety standards. In this context, safety signs play a fundamental role in communicating hazards and educating employees on the proper procedures to act in emergency situations. Safety signs inform about dangers, indicate evacuation routes, and remind people to wear appropriate personal protective equipment [1]. They can also be a factor in preventing accidents at work by providing appropriate information (it can be pointed out that many accidents are caused by organizational factors, such as insufficient provision of information about the hazard) [2, 3].

Typically, the most popular horizontal signs are used in companies, installed on floors, on walls and columns of production halls. It is certainly the easiest solution to provide information about the evacuation route or hazard, however, employees often do not pay due attention to them. It is certainly crucial to install signs of the right size for the place of installation and to select the right sign for the message being conveyed. In order to engage employees in receiving information presented through signs, interactive signs are increasingly used, which are more visible to the employee and at the same time engage them by providing an element of curiosity about the specific operation of individual components [4, 5].

This article presents the concept of using interactive safety signs in the context of managing traffic inside a selected production hall. The first phase of the research was to analyze the possibility of installing such safety signs, taking into account the location of machines and communication routes. Then, a proposal for the location of interactive signs was presented, together with an indication of the resources necessary for this installation. The conducted research allowed to determine the possibility of using interactive signs in the management of internal traffic (pedestrians and forklifts) in a place defined as particularly dangerous from the point of view of the location of communication routes and gates. The impact of the applied solutions on the occurrence of accidents in this place and encouraging employees to move in accordance with the established rules was also determined.

2 SAFETY SIGNS IN THE CONTEXT OF MANAGING IN-PLANT TRAFFIC

2.1 Legal Requirements for Safety Signs

Council Directive 92/58/EEC defines safety and/or health signs as *signs referring to a specific object, activity or situation and providing information or instructions about safety and/or health at work by means of a signboard, a color, an illuminated sign or acoustic signal, a verbal communication or a hand signal, as the case may be*. It also indicates the division of signs and the need to use them in situations that require providing employees with understandable messages [6]. Many international and national legal regulations indicate the need to inform employees about hazards and the required behavior in a given place. Safety signs are partly standardized by the ISO 7010:2020-07 standard, which is part of the international signage system. This document contains a set of standard graphic symbols that are used to communicate information about hazards and safety rules. Signs are divided into the following categories: prohibition, warning, order, evacuation, first aid, fire protection and information. Another division of signs refers to the transfer of information to recipients and indicates light, acoustic, verbal and hand-indicated signs in the absence of the possibility of providing a physical sign. By using appropriate colors and shapes, the signs are to be understandable to every recipient (even without knowledge of e.g. the language of communication) [7, 8].

2.2 Approaches Used to Provide Safety Signs

It is advisable to take into account the safety signs not only due to legal requirements, but also for the purpose of obtaining other benefits, e.g. making employees aware of the most significant hazards identified in the production process or systemic management of traffic within the plant [9, 10]. Internal traffic management is implemented through communication between employees and the production and logistics system (including internal transport) in terms of determining, for example, priority of passage, communicating hazards on the machine or the need to stop at a designated place before continuing to the destination [11]. Many companies provide standard horizontal signs, of appropriate size depending on where they are installed. This is a simple and relatively cheap solution due to the easy availability of signs (also with additional functions, e.g. fluorescent). The perception of these signs may depend on their size, but also on their color and whether they warn about a given type of hazard [12].

Current employee safety management requires the use of new solutions in the field of hazard information due to dynamically developing processes but also due to employees becoming accustomed to standard safety signs (which often results in them being omitted). Companies are increasingly using interactive signs to enhance the effect of influencing employee behavior by creating an element of curiosity and ensuring that the sign operates at the right moment to focus attention (e.g. when a machine opens or a forklift passes by) [13]. The meaning of messages conveyed through signs and how they work is presented to employees during training and in direct conversations with their superiors [14]. The examples of the interactive sign are shown in Fig. 1-3.

Figure 1 Example of interactive safety sign [15]

Figure 2 Example of interactive safety sign [own photography]

Figure 3 Example of interactive safety sign [own photography]

By displaying signs as intended, it is possible to inform employees about important aspects of the process (mainly hazards) but also to manage the traffic of e.g. forklift operators by passing on a message e.g. about when to stop. It can therefore be indicated that information signs will perform various functions in managing internal traffic [15-17]:

- providing an information function for employees moving around the production hall on foot (e.g. "STOP" signs, warning about a forklift passing by, order to use personal protective equipment),
- causing forklift operators to stop, e.g. at intersections or places of increased pedestrian traffic,
- traffic management by indicating e.g. places prohibited for pedestrians or additional crossings (additional illumination of their course),
- additional lighting at intersections where an accident or collision may occur,
- informing about the possibility of passing by the machine or the impossibility of doing so, e.g. due to the delivery of goods or ongoing repair or maintenance activities.

Often, signs are installed in a way that allows them to be activated only when movement is detected on internal roads. This results in savings related to the lack of their continuous operation but also increases the employees' attention to their appearance.

In the undertaken research the case of the possibility of using an interactive intersection was analyzed. The problem and its proposed solution are presented graphically in Fig. 4.

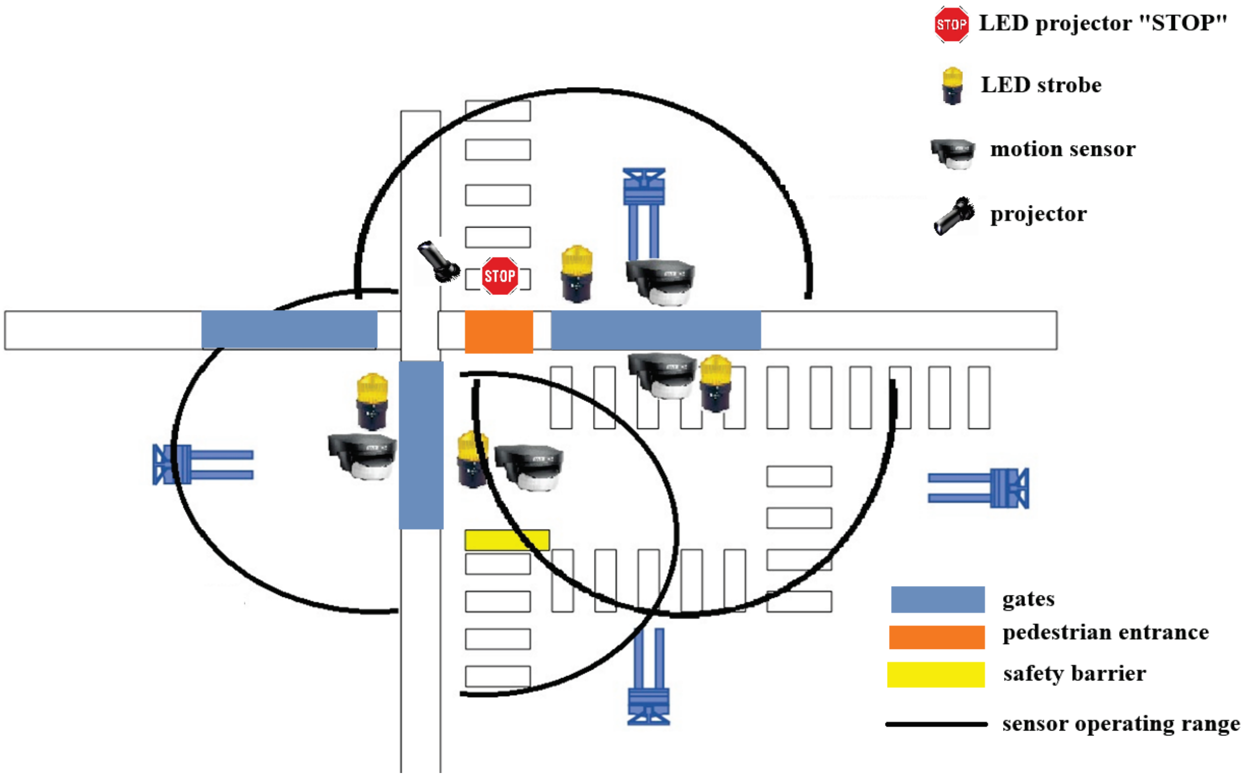

Figure 4 Proposed solution to the research problem [own elaboration in MS Visio]

3 METHOD OF RESEARCH

The research undertaken was aimed at solving the problem of increased internal traffic in a selected location in the company through the appropriate use of interactive signs. The main problem identified was the close location of three transport gates (where forklifts move) and pedestrian crossings near these gates. Approximately 200 pedestrians and 35 forklift operators take part in internal traffic during a work shift. The machines are located directly next to the communication road (approx. 70 cm) on the side of the pedestrian crossing.

The following project implementation results were assumed:

- directing pedestrian traffic on designated roads so that they choose a pedestrian crossing in the appropriate direction of moving,
- ensuring that forklift operators are informed about pedestrians moving on the road,
- ensuring that signals are understandable to both pedestrians and forklift operators and clearly visible,
- combining the operation of all elements of the proposed solutions (sensors and projectors) with simultaneous cost reduction and their operation only when traffic is detected on internal roads,
- ensuring the possibility of training all participants in internal traffic in the operation of the proposed solution in order to eliminate errors in the reception of transmitted information.

Due to the location of the gates and pedestrian crossings, it was decided not to provide only standard horizontal signs informing about the way of moving and caution. However, they were also installed from the point of view of meeting the requirements of legal regulations.

The solution to the problem presented in the article was developed in cooperation with process engineers and employees moving around the hazardous area on a daily basis, which had to be additionally marked. The following sections describe the mechanism of operation of the proposed solution as well as discuss its effectiveness and implementation barriers.

4 RESULTS

The presented solution assumes the safety of pedestrians and forklift operators at a particularly dangerous intersection due to the proximity of three gates and pedestrian crossings. A solution was proposed, which is a combination of several LED strobes and a projector displaying the "STOP" sign at the pedestrian crossing before entering the communication route. The operation of the devices presented can be described as follows:

1) In the event of a forklift approaching the intersection, the motion sensors detect it and activate the stroboscopes, which inform pedestrians about the hazard (using an orange light) that may appear on the road while they are crossing the pedestrian route.
2) In the case of informing forklift operators about pedestrians on the other side of the gate, the solution works on a similar principle - if a pedestrian appears, the

motion sensor detects it, informing the forklift operator about it with an orange light. The motion sensors detect a pedestrian entering the pedestrian crossing, so the operator has enough time to react if the signal appears.

3) The most dangerous exit to the described internal road was the entrance, where it was required to provide an additional sign about stopping before crossing the door. A LED "STOP" sign with a projector displaying it was provided there. If a forklift movement is detected on the other side of the passage, the large sign is displayed on the ground, urging the employee to stop and pay special attention to the movement of forklifts on the road. The sign appears only when a forklift movement is detected, so it does not appear all the time so as not to accustom employees to its presence (as in the case of standard horizontal signs).

Additionally, to increase safety, a barrier was installed at a greater distance from the intersection, which forces the employee to slow down when approaching the intersection. The approximate range of motion sensor operation is shown in Fig. 4. The methods of operation were determined based on measurements of the distance of the sensors from the gates and pedestrian crossings, as well as on calculations of the time required for the forklift operator to stop or slow down enough to avoid a collision with a pedestrian near the pedestrian path.

The implementation was completed with employee training explaining the operation of the proposed improvements at the intersection and on the traffic routes. While the operation of the projector and the "STOP" sign was understandable to everyone, the operation of the visual aspects (orange lights) had to be thoroughly explained and presented in real conditions.

5 DISCUSSION

The presented solution of installing an interactive sign and light signals made it possible to achieve the implementation goals, which were mainly to increase safety and manage internal traffic in a selected area with increased risk. Employees were informed about how to move around this area, and their attention was also drawn to threats through an interactive element. In relation to in-plant traffic management, it became possible to direct the movement of forklifts in terms of adjusting the speed to pass through gates and to exercise caution in the context of the possibility of pedestrian traffic on pedestrian paths near gates.

Despite achieving the goal, it is possible to indicate many implementation limitations that resulted from the need to provide appropriate resources and the analysis of benefits in relation to standard solutions (e.g. providing horizontal signs). These limitations are presented in Tab. 1.

Taking into account the above-mentioned limitations of implementing a solution with interactive elements, it can be stated that it requires a detailed analysis in order to ensure an optimally functioning system, taking into account financial possibilities as well as the expected result of the implementation. Sometimes it may turn out that the adopted assumptions may not be met due to insufficient resources or limited employee involvement in the process.

Table 1 Limitations of the solution proposed in the analyzed case study

No.	Limitation	Analysis of the impact of the limitation on the final proposal to solve the research problem
1	Much higher implementation costs than providing standard horizontal markings.	Providing horizontal safety signs on the production floor is a relatively cheap solution. For this reason, in the case of the planned solution with interactive elements, an analysis of the benefits had to be carried out in relation to the higher costs to be undertaken (approx. 20 times higher). It was decided that the possible increase in employee safety is a factor that can compensate for the higher cost of implementing the proposed system.
2	The need to find and connect modules that provide detection of pedestrians and forklift movement.	It was decided that the solution would consist of separate modules and the whole thing was installed by maintenance engineers. Their task was to find the right devices and connect them, which increased the implementation time to several weeks.
3	The need to perform detailed calculations to determine the location of motion sensors.	Motion sensors were installed after calculating the time needed for a forklift operator to slow down or stop. Determining this time and distance applied to all gates and pedestrian crossings in the designated dangerous location. It was also necessary to determine the height and size of the light signs, as well as the distance of the LED "STOP" sign from the entrance door leading to the intersection.
4	The need to determine whether it is necessary to engage an external company to complete the order or whether it will be done internally.	It was decided that the implementation would be done internally by maintenance engineers due to the lower costs of interfacing the system components. This decision was preceded by obtaining offers from external companies in this area, which turned out to be much higher than matching different devices.
5	The implementation of the proposed system may not solve the problem of unsafe employee behavior and crossing the road in prohibited places.	Considerations were made on whether the implementation of the proposed solution would significantly affect the behavior of employees in the dangerous area of the intersection. People are the least predictable element of internal traffic, therefore it was wondered whether the costs incurred for the implementation would be adequate to the result obtained. The opinion on this subject was expressed by the employees' superiors, and a training element was also carefully planned after the solution was implemented. It was stated that the actions taken should contribute to increased caution on the part of employees. However, this requires verification after some time of using the solution in order to consider taking further actions to increase the awareness of participants in internal traffic.

Source: own elaboration.

6 CONCLUSIONS

Employee safety in the production process is an extremely complex issue because, in addition to organizational resources, it also requires the involvement of all participants in the issue of safety, from employees operating machines to their superiors. This is particularly important in the case of organizing internal traffic (pedestrians and e.g. forklift operators). One of the elements of ensuring their safety is to inform about threats and required behaviors in a given place, which can be done by providing appropriate safety signs. In addition to standard horizontal safety signs, it is possible to install interactive solutions, the advantage of which is certainly to provide an element of interest and greater visibility of a given threat.

As shown in the above example, solutions with interactive elements can be a response to identified problems in ensuring safety in places where there is increased traffic at dangerous intersections and pedestrian routes, which for technological or organizational reasons could not be routed in a different, safer way. The aim of their implementation is to increase employees' attention to threats by implementing systems to which they are not accustomed as they are to standard solutions. An additional advantage of such systems can be the management of internal traffic by influencing, for example, the direction of pedestrians or the speed adopted on a forklift. However, this requires that all elements be properly matched and installed at appropriate distances to properly detect movement and then transmit messages at the right time.

There is no doubt that implementing interactive solutions involves higher costs than in the case of standard safety signs. This is certainly one of the limitations of implementing such solutions, especially in production halls where there are many places that are potentially dangerous for employees. Another important limitation to consider is the need to find and connect appropriate modules in order to obtain the desired effects of introducing such a system. For this reason, each such improvement should be preceded by an appropriate analysis of the needs and possibilities of appropriately adjusting individual elements.

It should be noted here that in the era of dynamically developing artificial intelligence, safety solutions that go beyond the standard and requirements of legal regulations will increasingly appear in modern enterprises. Their recognition and implementation can facilitate faster adaptation to these changes by employees and also build a competitive advantage for the organization on the labor market.

7 REFERENCES

[1] Haleem A., Javaid M. & Singh R. P. (2025). Encouraging Safety 4.0 to enhance industrial culture: An extensive study of its technologies, roles, and challenges. *Green Technologies and Sustainability, 3*(3), 100158, https://doi.org/10.1016/j.grets.2024.100158

[2] Czernecka W. (2022). Including occupational risk assessment in the workstation description sheet as a factor contributing to increasing the risk perception of employees. *Proceedings of the 39th International Business Information Management Association Conference (IBIMA): Business Excellence and Innovation Management: A 2025 Vision to Sustain Economic Development in the Era of Pandemic*, 30-31 May 2022, Granada, Spain, 132-138.

[3] Guoa, H., Yua, Y. & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction, 73*, 135-144. https://doi.org/10.1016/j.autcon.2016.10.004

[4] Wu, S., Hou, L., Zhang, G. & Chen, H. (2022). Real-time mixed reality-based visual warning for construction workforce safety. *Automation in Construction*, 139, 104252. https://doi.org/10.1016/j.autcon.2022.104252

[5] Hozdić, E. (2015). Smart factory for industry 4.0: a review. *International Journal of Modern Manufacturing Technologies, 7*(1), 28-35.

[6] Council Directive 92/58/EEC of 24 June 1992 on the minimum requirements for the provision of safety and/or health signs at work.

[7] ISO 7010:2020-07: Graphic symbols - Safety colours and safety signs - Registered safety signs.

[8] *Safety signs and signals*. Health and Safety Executive (2015), 3rd Edition.

[9] Leveson, N. (2015). A systems approach to risk management through leading safety indicators. *Reliability Engineering & System Safety, 136*, 17-34, https://doi.org/10.1016/j.ress.2014.10.008

[10] Khan, L. U. (2017). Visible light communication: Applications, architecture, standardization and research challenges. *Digital Communications and Networks, 3*(2), 78-88. https://doi.org/10.1016/j.dcan.2016.07.004

[11] Barretoa, L., Amarala, A. & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. *Procedia Manufacturing, 13*, 1245-1252, https://doi.org/10.1016/j.promfg.2017.09.045

[12] Bian, J., Fu, H. & Jin, J. (2020). Are We Sensitive to Different Types of Safety Signs? Evidence from ERPs. *Psychology Research and Behavior Management, 13*, 495-505. https://doi.org/10.2147/PRBM.S248947

[13] Badri, A., Boudreau-Trudel, B. & Saâdeddine Souissi, A. (2018). Occupational health and safety in the industry 4.0 era: A cause for major concern? *Safety Science, 109*, 403-411. https://doi.org/10.1016/j.ssci.2018.06.012

[14] Li, H., Lu, M., Hsu, S. C., Gray, M. & Huang, T. (2015). Proactive behavior-based safety management for construction safety improvement. *Safety Science, 75*, 107-117. https://doi.org/10.1016/j.ssci.2015.01.013

[15] https://www.compliancesigns.com/pd/5s/24-inch-double-sided-interactive-flashing-safety-sign-with-1-motion-detector-15si24ds, accessed: 28.12.2024

[16] https://elmetal.pl/produkt/interaktywne-znaki-i-bramki-led/, accessed: 28.12.2024

[17] https://www.cisco-eagle.com/product/185185/double-sided-24-interactive-led-safety-sign, accessed: 28.12.2024

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Additive Manufacturing: A Key to Advancing Injection Molding Efficiency

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Abstract: The increasing demand for custom-made products, small-batch production, and improved process efficiency is driving manufacturers to adopt advanced strategies that minimize costs and production time. Additive manufacturing (AM) technologies address these challenges by enabling rapid prototyping, design flexibility, and advanced tooling capabilities. Initially constrained to polymeric prototypes, AM now supports a diverse material range, including metals and temperature-resistant polymers. Injection molding is a widely used manufacturing process for producing plastic parts with high precision and repeatability. However, traditional injection molding faces challenges such as high tooling costs, long lead times, and design limitations. This paper investigates solutions to these challenges through the application of additive manufacturing and rapid tooling technologies, emphasizing their potential to transform efficiency in injection molding.

Keywords: additive manufacturing; conformal cooling channels; injection molding; rapid prototyping

1 INTRODUCTION

The manufacturing industry has witnessed transformative changes in recent decades, with the integration of advanced technologies playing a pivotal role in improving efficiency, reducing costs, and enabling innovation. Among these technologies, Additive Manufacturing (AM), also known as 3D printing, has emerged as a transformative force that is reshaping traditional production processes. Initially developed as a prototyping tool, AM has evolved into a robust and efficient technology capable of rapidly producing fully functional end products (additive/direct manufacturing) and tooling components (rapid tooling) [1, 2]. It offers advantages such as shortened lead times, cost savings, and enhanced design flexibility, alongside a broad material selection, including polymers, metals, ceramics, and composites, all while minimizing material waste [3]. On the other hand, the main challenges of AM technologies involve limitations in part accuracy, surface quality, strength, durability, size, and production speed.

The term rapid tooling (RT) encompasses processes that employ AM technologies to produce tooling components, including cavities, cores, inserts, dies, molds, ejectors, sliders, gauges etc. While RT is sometimes considered a distinct application level within AM technologies, it is not entirely independent [4]. RT eliminates many of the bottlenecks associated with conventional tooling production, such as extended lead times and high total costs.

There are two main levels of AM application in tooling production, based on tool quality and functionality: Hard Tooling (HT) and Soft Tooling (ST). HT involves creating fully functional tools for high-volume production directly from CAD models using AM and high-strength materials such as steel and aluminium. This approach enables the fabrication of highly complex mold shapes with enhanced durability. ST includes tools designed for single or small-batch production. Soft tooling, commonly made from substitute materials, generally does not match the durability of hard tooling but offers significant cost savings. This makes it a practical choice for applications involving frequent design changes or low-volume production requirements. For instance, in injection molding, a soft tool typically lasts between 100 and 1,000 shots [5, 6]. Fig. 1 provides a graphical representation of the number of cycles for molds produced using conventional tooling as well as AM-based technologies, plotted against the workpiece material. In some cases, ST tools are categorized as a subset of HT tools and referred as Bridge Tools (BT) [3]. In general, the quality of rapid tooling produced through AM is primarily determined by two factors: the material used and the AM technology employed. It is important to note that HT and ST do not mean the entire tool assembly is made via AM. Typically, only specific, non-standard tool components are manufactured using AM and then combined with conventional tool elements to form a complete, functional assembly.

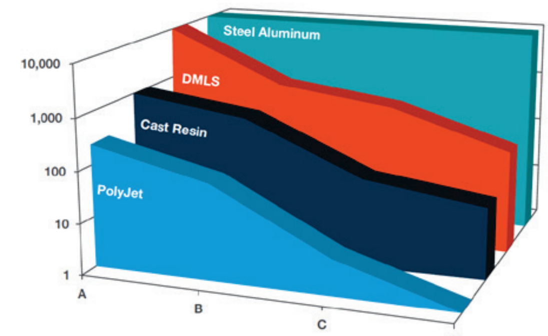

Figure 1 The number of parts manufactured using molds produced by conventional and AM technologies [8] (A - PE, PP, PS, ABS, TPE; B - PP+G, PA, POM, PC+ABS; C - PA+G, PC, POM+G; D - PC+G, PPO, PPS)

The ISO/ASTM 52900 standard [7] classifies AM technologies into seven distinct families or categories, each defined by the fundamental process used to build parts. These categories encompass a wide range of techniques, including material extrusion, powder bed fusion, vat photopolymerization, binder jetting, directed energy deposition, sheet lamination, and material jetting. However, not all AM methods are suitable for producing tools and tooling components. Each AM technology comes with its own advantages and limitations, which can substantially influence the final tool's performance and service life. Selecting the optimal AM technology depends on the type of tool and the associated techno-economic requirements. It is important to note that AM molds must meet far more rigorous standards than conventional AM components to withstand the intense mechanical and thermodynamic loads during use.

HT, which involves the production of tool components from metal materials, commonly utilizes AM technologies such as Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). On the other hand, ST components, primarily made from polymeric materials, are typically manufactured using Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS) and, PolyJet techniques.

This paper provides an in-depth analysis of the benefits AM brings to injection molding processes and presents selected results from its application in mold production. Additionally, it highlights challenges of applying AM in mold manufacturing.

2 OVERVIEW OF THE BENEFITS OF IMPLEMENTING AM TECHNOLOGIES IN INJECTION MOLDING TOOLING

Injection molding is a widely used manufacturing process, renowned for its ability to produce high volumes of complex plastic parts with consistent quality. However, it is not without its challenges. The process often involves significant lead times, high tooling costs, and limited flexibility for design modifications, which can hinder manufacturers' ability to respond quickly to market demands and innovation opportunities. AM addresses these challenges by providing innovative solutions that enhance the efficiency and adaptability of injection molding processes.

2.1 Fast Mold Prototyping and Enhanced Small-Batch Production Efficiency

AM allows manufacturers to quickly prototype molds and components, enabling rapid iteration and testing. This significantly reduces the time between design and production, allowing manufacturers to respond more flexibly to market demands and reduce the risk of costly errors. According to Whelan and Sheahan [9], the use of AM/RT can reduce product development costs by up to 70% and decrease time to market by as much as 90%. Levy et al. [5] presented similar findings, demonstrating that the application of AM in producing mold components, such as core and cavity, led to a 50–70% reduction in both the time and cost associated with mold development and design. The ability to easily modify mold designs and create customized solutions also opens up opportunities for smaller production runs and more tailored products. This is particularly beneficial for industries such as healthcare and aerospace, where custom components are often required. AM also supports on-demand mold production, a crucial advantage for industries that require custom components. In other words, AM and RT have the potential to resolve the challenges encountered by design engineers and manufacturers in balancing part design, manufacturability, and small-batch production.

2.2 Improvements in Mold Design, Manufacturing, and Performance

One of the most significant contributions of AM to injection molding is in mold design [3, 9]. Conventional injection molds require a substantial investment of time and resources to design and manufacture. The process often involves CNC machining, which can be limited by the complexity of mold features and the time required for tool manufacturing. AM, however, allows for advanced mold designs and the production of molds with complex geometries and cooling structures that are difficult or impossible to achieve with conventional techniques [2]. This includes complex cores and cavities, conformal cooling channels, intricate lattice structures, and lightweight features. As a result, cycle times are shorter, warping is minimized, part quality is improved, and scrap rates are reduced.

2.3 Reduction in Mold Weight

Large molds are commonly used in industries such as automotive, aerospace, and household goods [10]. However, their size and complexity introduce significant challenges, including excessive weight, high unit costs, and safety risks. The use of AM-created lattice structures has emerged as a promising solution for reducing mold weight while maintaining mechanical strength and functionality.

2.4 Multi-Material Printing and Material Efficiency

AM enables the simultaneous printing of molds using multiple materials [4], a capability particularly valuable when different regions of a mold require distinct properties. Multi-material printing facilitates the integration of characteristics such as varying hardness, thermal conductivity, or wear resistance. For instance, a mold may feature a hard, durable surface in high-wear areas while incorporating a softer, more flexible material in sections requiring intricate detail.

In terms of material efficiency, AM provides a significant advantage over traditional machining by substantially reducing material waste. Material waste can be cut by up to 90% with AM [1, 11], making it a more sustainable and cost-effective manufacturing method.

2.5 Mold Maintenance and Repair

AM can be employed to repair or modify molds, effectively extending their operational life and reducing downtime [6]. By using AM, damaged areas of molds can be accurately repaired, and design updates can be seamlessly integrated without requiring complete tool replacement.

2.6 Smart Molds

Using AM technologies, sensors and heating elements can be seamlessly incorporated into the mold structure without compromising its durability or functionality [12]. These feature provide real-time monitoring and control of the molding process, including temperature, pressure, and flow rates, to maintain optimal production conditions.

2.7 Hybrid Manufacturing

The integration of AM with conventional manufacturing methods provides innovative solutions for enhanced efficiency. By utilizing AM to produce near-net-shape molds and CNC machining for final finishing, complex geometries can be created with minimal material waste while achieving high accuracy and superior surface quality in critical areas.

3 SOFT AND HARD TOOLING SOLUTIONS FOR MOLDING

In prototype and low-volume production (soft tooling), a universal metal base combined with polymer-based inserts (core and cavity) is commonly used. This modular approach allows a single master base to support multiple insert designs. Additionally, the robust metal base enhances structural integrity, enabling a reduction in the size of polymer core and cavity inserts, which results in faster production and reduced material waste. To optimize the performance of polymer inserts, the mold base geometry should be slightly adjusted compared to designs intended for metal inserts. Mold features such as draft angles, radii, and gate size should be increased as much as possible, while sprue and ejector holes should be undersized by 0.2-0.3 mm. As for runners and cooling channels, standard sizing practices should be followed when dimensioning [2].

Molds with polymer inserts are not without limitations. While they are well-suited for prototyping, low-volume production, or specific applications where extreme durability is not required, they may not withstand the high pressures and temperatures associated with large-scale or high-volume part manufacturing as effectively as metal molds. Therefore, one of the key challenges in developing an AM process for molds with polymer inserts is selecting materials that provide the necessary mechanical and thermal properties of mold. The differing thermal responses of polymers inserts during the injection and cooling stages require precise control to avoid tolerance loss and deformation of the workpiece. The service life of a polymer mold depends on several factors, including the mold material, the complexity of the tool /workpiece geometry, melted polymer properties, injection molding process parameters, wear etc. Another challenge in AM molds is surface quality, as the layer-by-layer manufacturing process can introduce roughness that necessitates additional finishing steps.

In addition to the previously mentioned drawbacks, polymer molds also provide several advantages over metal molds, including: reduced clamping force, improved air barrier performance, and better ventilation. Ventilation conditions can be further optimized with the use of multi-part molds (Fig. 2), which improve their service life [8]. Multi-part molds are particularly beneficial for molds with complex geometries, where damage to individual segments can occur due to small sections and sharp corners. Additionally, they offer the advantage of quick replacement if individual components break or deform. To enhance the operational performance of molds with polymer inserts and extend their service life, it is crucial to carefully select injection molding process parameters, including temperature, pressure, and cycle time. In other words, adjustments to the parameters used for conventional (metal) inserts should be made, and their upper limits must be defined to prevent mold damage. In general, it is recommended to select standard processing parameters for injection pressure, mold temperature, and melt temperature of industrial polymers at the lower end of the recommended ranges. In terms of injection pressure, the rate at which it increases is also important. Applying the standard injection pressure adjustment procedure, which involves a rapid increase to maximum pressure, could result in the displacement of inserts and their undesirable deformations, leading to improper mold functioning. Therefore, the injection pressure should be gradually increased and generally kept as low as possible. Similar recommendations apply to the holding pressure.

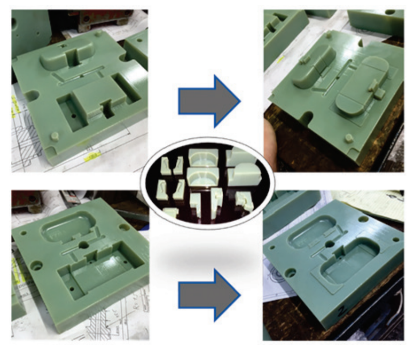

Figure 2 Multi-part molds produced using the PolyJet process [8]

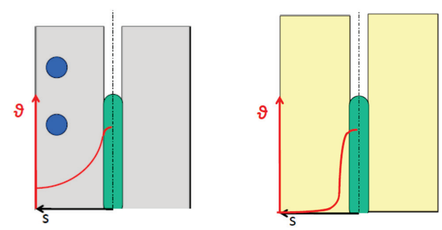

Figure 3 The temperature profiles of the metal (left) and polymer (right) molds [13]

Cooling time is another critical factor, as it directly affects both the efficiency of the injection molding process and the service life of the mold. Due to the lower thermal conductivity of molds with polymer inserts compared to traditional metal molds, the cooling time is significantly longer to prevent thermal damage to the molds. Fig. 3 illustrates the temperature distribution across the cross-section of conventional (metal) and polymer mold inserts. As seen in Fig. 3, heat distribution is more uniform in the metal insert (Fig. 3 - left) compared to the polymer insert, where heat accumulates near the mold parting line. This leads to a higher thermal load on the insert surface, increasing wear and sticking while raising the risk of warping or cracking. To minimize wear, it is crucial to extend the cooling phase (time) after part ejection and, if possible, reduce the wall thickness. On the other hand, a slow cooling rate increases the crystallinity of the molded part, enhancing its strength, dimensional stability, and aesthetic appearance. Besides this, slower cooling contributes to lowering internal stresses, ensuring improved strength and reliability of the molded part. In this regard, polymer molds offer advantages over metal molds. It is important to note that cold compressed air is commonly used during the open mold time to keep mold insert temperatures below the heat deflection temperature (HDT). This approach offers greater cooling efficiency compared to traditional cooling channels, which may compromise the stiffness of a polymer mold.

Fused Deposition Modeling (FDM) is the most accessible form of 3D printing. Although FDM employs a wide range of materials, only a few materials, such as Acrylonitrile Butadiene Styrene (ABS), ABS-X, Acrylonitrile Styrene Acrylate (ASA), PolyEther Ether Kentone (PEEK), Polyether Imide (PEI) - ULTEM, and several nylons, meet the operational demands of injection molding. Furthermore, producing parts from these materials requires specialized printer capable of achieving high nozzle temperatures (above 300 °C), heated build plates (above 100 °C), and, in some cases, a high ambient temperature of over 170 °C [14]. Despite its advantages, FDM-based mold manufacturing faces notable obstacles, such as high surface roughness and structural weaknesses in the gate area, which experiences extreme thermal and pressure conditions. As a result, these inserts typically last no more than 10 injection molding cycles before sustaining damage, primarily at the gate. In contrast, tools and molds produced using SLA, DLP, and SLS exhibit greater resistance to high temperatures and pressures. While all these methods enhance mold durability, SLA and DLP offer a smoother surface finish compared to SLS, typically requires. Moreover, SLA and DLP are generally more cost-effective, making them a more attractive option for various applications.

In its early stages, SLA was mainly used to create solid resin molds for prototyping and small-scale production (up to 50 pieces) of simple, small components made from low-abrasion, low-melting-point thermoplastics. This process is known as direct SLA or Accurate Clear Epoxy Solid (ACES) injection molding (AIM) tooling, where both the core and cavity are fabricated directly using a stereolithography machine. Thanks to advancements in SLA resin technology, primarily through the introduction of acrylic, vinyl, and epoxy-based resins that can withstand higher operational temperatures, SLA has significantly enhanced its ability to produce mold inserts with improved performance and longer service life (up to 200 cycles), as well as to mold parts from a wider range of materials. SLA mold production has been further enhanced with the introduction of shell tooling, commonly referred to as backfilled molds. This process begins with the creation of an SLA shell with a wall thickness of 2–3 mm, which is then reinforced with thermally conductive materials such as aluminum-filled epoxy (a blend of 70% epoxy resin and 30% aluminum powder) or a low-melting metal alloy to form the injection molding tool (Fig. 4). This mold not only provides improved thermal conductivity and service life (allowing for 50–500 cycles of materials at melting temperatures up to 300 °C) but also reduces tooling development costs compared to molds produced using the direct SLA method.

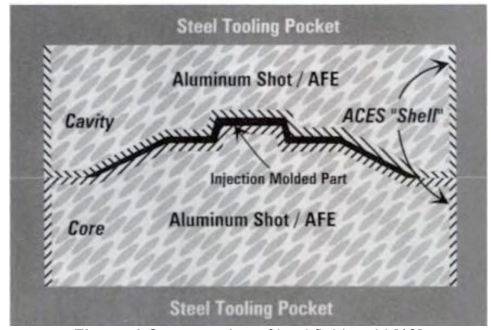

Figure 4 Cross section of backfield mold [13]

Similar to SLA, PolyJet mold inserts are most effective for thermoplastics that melt at low to moderate temperatures (below 300 °C) and demonstrate excellent flow characteristics, including polyethylene (PE), polypropylene (PP), polystyrene (PS), acrylonitrile butadiene styrene (ABS), thermoplastic elastomers (TPE), polyamides (PA), polyoxymethylene (POM), PC-ABS blends, and glass-filled resins [15]. PolyJet molds are best utilized in small-batch production (typically 5 to 100 molded parts - see Fig. 1) and for small to medium-sized components with volumes up to approximately 150 cm³. The poor heat conductivity of PolyJet molds limits the effectiveness of cooling systems in reducing molding cycle times or improving part quality, but they can extend tool life by up to 20% [15]. This improvement is more noticeable as the cavity depth and core height decrease. Mendible et al. [16] compared conventionally manufactured metal inserts to those made using DMLS (metal) and PolyJet (polymer) technologies, as shown in Fig.5. The findings reveal that DMLS inserts closely matched the performance of machined inserts, with no evident signs of failure after 500 cycles. In contrast, PolyJet inserts began producing defective parts at 80 cycles and failed completely by 116 cycles. Additionally, PolyJet mold exhibited the highest shrinkage variance, along with extended cycle times and notable temperature gradient.

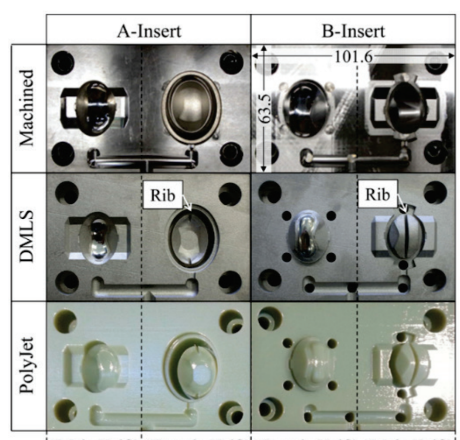

Figure 5 Mold inserts manufactured using different technologies [16]

In injection molding process, the reduction in cycle time is heavily influenced by the design (conformability) of the cooling channels and the complexity of the part. Unlike traditional straight-line cooling channels, conformal cooling channels (CCCs) are designed to follow the contours of the mold, ensuring more uniform heat removal and efficient cooling. This results in shorter cycle times and enhanced production efficiency. According to studies [6, 10, 17], conformal cooling channels (CCCs) can reduce cycle times by up to 50%, with certain applications reporting reductions of up to 70%, as noted by Evens et. al. [18]. These channels also enhance surface finish quality, minimize shrinkage and deformation, reduce the average time required to reach ejection temperature by over 30% compared to conventional cooling methods, and lower the maximum temperature on the mold surface by up to 20-30% [19].

One of the key advantages of CCCs is their ability to provide a more uniform temperature distribution across the mold surface, effectively reducing hot spots - localized areas with elevated temperatures that can negatively impact product quality. By optimizing heat dissipation, CCCs contribute to improved dimensional stability and reduced internal stresses within molded parts. In terms of economic benefits, a 20–40% reduction in cooling time can result in an estimated 27–55% increase in profit margins. Additionally, product quality improvements of up to 70% have been reported when CCCs are implemented in the injection molding process [17].

However, while CCCs enhance cooling efficiency, their complex design can introduce challenges. The intricate pathways result in higher coolant pressure drops than conventional channels, leading to increased energy consumption from the cooling system. This trade-off between cooling time reduction and temperature uniformity underscores the importance of proper CCC design and optimization before real-world implementation.

The CCCs are predominantly integrated into molds that feature metal inserts (core and cavity), which are manufactured using AM powder bed fusion (PBF) technologies. In addition to common PBF-related challenges such as porosity, residual stresses, and rough surfaces, a critical concern in manufacturing molds with CCCs is the risk of collapse and warping of overhanging structures, particularly in large holes and channels. To ensure structural integrity during printing, support structures are often required. However, removing these supports and clearing residual powder from internal channels can be difficult due to their complex geometries and small diameters. If left inside, they can obstruct coolant flow and reduce cooling efficiency. To address this issue, molds featuring self-supporting CCCs and tailored porous structures, incorporating high-strength diamond units, have recently been designed and manufactured (Fig. 6) using AM-PBF technology [20].

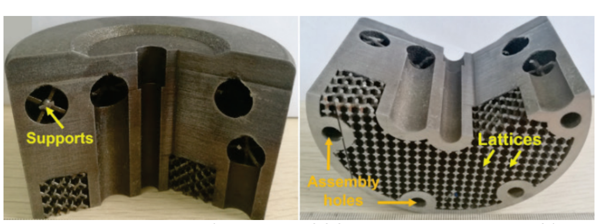

Figure 6 Mold with self-supporting CCCs and porous structures [21]

As it said before, AM technology allows for the precise design and fabrication of complex lattice structures that optimize material distribution within the mold. Study [21] confirmed the effectiveness of lattice structures in reducing mold weight, achieving an impressive 79% reduction compared to a solid Ti-6Al-4V mold using octet-truss (OT) and diamond (DM) configurations (Fig. 7). The redesigned mold also proved highly durable, completing 400 PVC injection cycles without any visible damage. Furthermore, lattice structures can be utilized to enhance both the structural integrity and thermal management of molds. By incorporating conformal cooling layers (Fig. 8) composed of interconnected scaffolds or porous elements, these structures enable heat transfer fluids to flow as close as possible to the molding surface. [22, 23]. Brooks et al. [23] found that conformal cooling layers can reduce cooling time by up to 27% compared to conventional cooling channels.

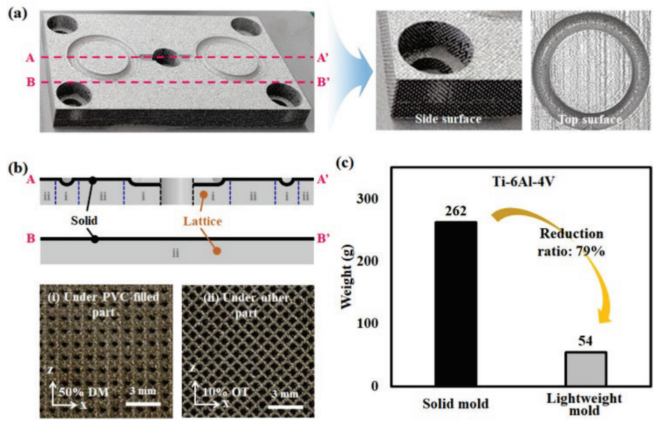

Figure 7 Additively manufactured mold with a lattice structure (a), sectional view illustrating step height (b), weight comparison between solid and lightweight Ti-6Al-4V molds (c) [22]

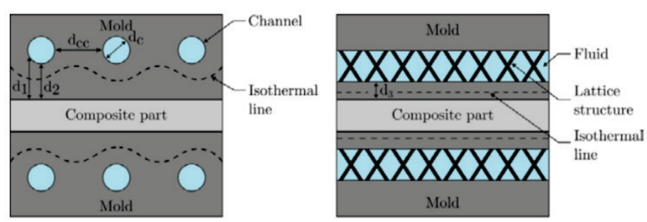

Figure 8 Schematic representation of (a) conventional cooling channels and (b) conformal cooling layers. [23]

4 CONCLUSION

Technological advancements in AM and RT have the potential to reshape the injection molding industry. By enhancing mold design, reducing prototyping time, and improving production efficiency, AM is addressing many limitations of traditional mold manufacturing. However, challenges remains. The durability of 3D-printed molds for high-volume production is still a concern, and the high cost of advanced AM systems can be a barrier for smaller manufacturers. Additionally, AM metal molds often require post-processing to achieve the required surface finish and dimensional accuracy.

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5 REFERENCES

[1] Gebhardt. A. (2011). *Understanding additive technology, rapid prototyping, rapid tooling, rapid manufacturing*. Hanser Publisher, Munich. https://doi.org/10.1007/978-3-446-43162-1

[2] Tuteski, O. & Kochov, A. (2024). SLA-based injection molding tool inserts: challenges, innovations, and future prospects. *Advanced technologies and materials, 49*(2), 29-36. https://doi.org/10.24867/ATM-2024-2-003

[3] Jacobs, P. F. & Hilton, P. D. (2000). *Direct AIM rapid bridge tooling in rapid tooling: technologies and industrial applications*, New York: Marcel Dekker.

[4] Chua, C. K., Leong, K. F., Liu, Z. H. (2015). *Rapid tooling in manufacturing*. Handbook of Manufacturing Engineering and Technology, London, Springer London, 2525-2549. https://doi.org/10.1007/978-1-4471-4670-4_39

[5] Levy, G., Schindel, R. & Kruth, J. P. (2003) Rapid manufacturing and rapid tooling with layer manufacturing technologies: state of the art and future perspectives. *Ann. CIRP, 52*(2), 589-609. https://doi.org/10.1016/S0007-8506(07)60206-6

[6] Rahmati S. (2014). Direct rapid tooling. *Comprehensive Materials Processing, 10*, 303-344. https://doi.org/10.1016/B978-0-08-096532-1.01013-X

[7] ISO/ASTM 52900:2021(en) *Additive manufacturing — General principles — Fundamentals and vocabulary*

[8] See https://www.customplastics.ca/wp-content/uploads/TAG_PJ_InjectionMolding.pdf

[9] Whlean, C. & Sheahan, C. (2019) Using additive manufacturing to produce injection moulds suitable for short series production. *Procedia Manufacturing, 38*, 60-68. https://doi.org/10.1016/j.promfg.2020.01.008

[10] Kuo, C. C., Zhu, Y. J., Wu, Y. Z. & You, Z. Y. (2019). Development and application of a large injection mold with conformal cooling channels. *International Journal Advanced Manufacturing Technology, 103*, 689-701, https://doi.org/10.1007/s00170-019-03614-4

[11] Turudija, R, Stojković, J. R., Stojković, M., Aranđelović, J. & Korunović, N. (2024). A multi-criteria decision-making approach for enhancing mechanical properties of FDM 3D-printed part. *Advanced technologies and materials, 49*(1), 25-31. https://doi.org/10.24867/ATM-2024-1-004

[12] Todorov, T., Todorov, G. & Romanov, B. (2019). Design and simulation of mould tools with multi-material structure for plastic injection moulding based on additive technology. *International Conference on Creative Business for Smart and Sustainable Growth (CREBUS)*, Sandanski, Bulgaria, 1-6. https://doi.org/10.1109/CREBUS.2019.8840061

[13] Stefanović, Lj., Milutinović, M., Movrin, D., Vilotić, M., Skakun P., Vilotić, M., Dačević N. & Ranđelović, S. (2020). Application of additive technologies for mold manufacturing in case of small-batch injection molding (in Serbian). *Proceedings of 42nd JUPITER conference*, Belgrade, Serbia, 3.35-3.60.

[14] See https://3dgence.com/filaments/ultem/

[15] Bagalkot A., Pons D., Glucas D. & Symons D. (2019). A methodology for setting the injection moulding process parameters for polymer rapid tooling inserts. *Rapid Prototyping Journal, 25*(9), 1493-1505. https://doi.org/10.1108/RPJ-10-2017-0217

[16] Mendible, G. A., Rulander, J. A. & Johnston, S. P. (2017). Comparative study of rapid and conventional tooling for plastics injection molding. *Rapid Prototyping Journal*, 23(2), 344-352. https://doi.org/10.1108/RPJ-01-2016-0013

[17] Kanbur, B. B., Zhou, Y., Shen, S, Wong K. H., Chen, C., Shocket, A. & Duan, F. (2022). Metal additive manufacturing of plastic injection molds with conformal cooling channels. *Polymers, 14*(3), 424. https://doi.org/10.3390/polym14030424

[18] Evens, T., Six, W., De Keyzer, J., Desplentere, F. & Van Bael, A. (2019). Experimental analysis of conformal cooling in SLM produced injection moulds: effects on process and product quality. *AIP Conf. Proc. 2055*, 070017. https://doi.org/10.1063/1.5084861

[19] Wang, Y. & Lee, C. (2023). Design and optimization of conformal cooling channels for increasing cooling efficiency in injection molding. *Applied Sciences, 13*(13), 7437. https://doi.org/10.3390/app13137437

[20] Tan, C., Wang, D., Ma, W., Chen, Y., Chen, S., Yang, Y. & Zhou, K. (2020). Design and additive manufacturing of novel conformal cooling molds. *Materials & Design, 196*, 109147. https://doi.org/10.1016/j.matdes.2020.109147

[21] Park, S. J., Lee, J. H., Yang, J. Heogh, W. Kang, D., Yeon, S. M., Kim, S. H., Son, H. Y. & Park, J. (2022). Lightweight injection mold using additively manufactured Ti-6Al-4V lattice structures. *Journal of Manufacturing Processes, 79*, 759-766. https://doi.org/10.1016/j.jmapro.2022.05.022

[22] Balthazar, M., Baudin, N., Soto, J., Guéroult, S. & Sobotka V. (2024). Improvement of thermal management of tooling using lattice structures: application to omega stringer mould. *Proceedings of the 21st European Conference on Composite Materials, ECCM21*, Nantes, France, 99-106.

[23] Brooks, H. & Brigden K. (2016). Design of conformal cooling layers with self-supporting lattices for additively manufactured tooling. *Additive Manufacturing, 11*, 16-22. https://doi.org/10.1016/j.addma.2016.03.004

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Influence of Innovative Digital Tools in Retail on the Purchasing Behaviour: An Empirical Study Based on a Customer Observation and on a Customer Survey

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Abstract: Digitalization is fundamentally changing the retail sector, presenting both companies and customers with new challenges and opportunities. Innovative digital tools, such as self-checkout systems, are becoming increasingly important and are not only influencing process efficiency but also the purchasing behaviour of consumers. This study examines the impact of digital innovations on the purchasing behaviour of customers in the retail sector and shows how modern technologies can supplement or even replace traditional structures. The aim of the study is to develop a deeper understanding of which factors promote or prevent the acceptance of digital systems and how these can be successfully integrated into practice. The study combines theoretical approaches with empirical findings in order to derive practical recommendations for the retail sector. Therefore, this study involves first observations in a supermarket aimed at capturing and interpreting consumer experiences in their natural context. Second a customer survey is conducted in the same supermarket. The findings reveal a picture of how digital tools, particularly self-checkout systems, influence customer purchasing behaviour in retail. In summary, while self-checkout systems offer significant benefits, their successful integration requires a balanced approach that addresses the diverse needs of all customer groups. By addressing these needs, retailers can maximize the efficiency and customer satisfaction of digital tools, ensuring their acceptance and long-term success in a rapidly evolving retail landscape.

Keywords: digital innovations; digital tools; purchasing behaviour; retail sector; self-checkout-systems

1 INTRODUCTION

Digitization has changed the retail sector enormously in recent years, with technological innovations such as self-checkout systems playing a key role. These systems allow customers to complete the payment process independently, potentially leading to shorter waiting times and a more efficient shopping experience. The retail sector is currently at an all-time high in the use of self-checkout technology. Over 5,000 shops in Germany already offer self-checkout options, an increase of 117 per cent compared to 2021 [1]. Despite this dissemination, questions remain about customer acceptance and the actual impact on purchasing behaviour. It is unclear how different customer groups react to this technology and what factors influence its use.

The aim of this study is to investigate how self-checkout systems affect people's shop-ping behaviour in the retail sector and what changes this technology brings to consumers' everyday lives. The focus is on analysing customer behaviour and preferences to better understand how these systems are used in practice and how they impact on the shopping experience. The goal of the study is to provide insights into the extent to which self-checkout systems are changing traditional shopping behaviour. It is looked on which factors determine the use of this technology in everyday life. This enables a deeper understanding of the interactions between customers and technology in the retail context.

2 LITERATURE REVIEW

2.1 Method and Focus of the Literature Review

The literature review of this study focuses on selected double blind peer-reviewed Journals included in VHB Rating 2024 [2] or in the "Resurchify" information portal [3]. The analysis presents an overview and insights into the research areas of digital innovation, retail management, and behavioural economics. A non-systematic literature review approach is applied, as it is more flexible and as it provides a broader overview [4, 5]. With regard to the selection of literature sources, the most important keywords which were searched were: "self-checkout" in connection with "supermarkets" or "technological progress". The search continued with "innovations in supermarkets", "customer behaviour in supermarkets" and "current changes in supermarkets". In the further process, it was searched for authors who have already published on the subject of "technology in retail". Due to this selection, a high-quality literature review could be carried out [6]. The four phases of designing, conducting, analysing and writing the review were employed to delve deeper into the fundamentals of "digitization in supermarkets" [7].

2.2 Retail, Digital Innovation and Customer Behaviour

Retail is a complex system that represents an exchange between sellers and end consumers, where products are provided to fulfil customers' needs. This requires a deep understanding of customer behaviour in order to create personalised shopping experiences and maximise the efficiency of sales channels. Today, a distinction is made between traditional retail and online retail (e-commerce). The current state of research in retail has changed significantly in recent years due to technological innovations and changing customer requirements. In particular, the integration of artificial intelligence (AI) and data-driven approaches plays a central role. The use of AI has expanded massively in the retail sector in recent years, enabling better analysis of customer behaviour and optimised processes [8]. Omni channel strategies in particular are a key element of modern retail research. Retailers are increasingly endeavouring to integrate various channels in order to meet changing customer preferences [9].

In order to achieve sustainable competitive advantages through efficiency and customer satisfaction, supermarkets are implementing more and more self-checkouts in practice [10]. As in practice consumers often favour technologies that are intuitive and convenient to use, supermarkets see great potential in this technology. Factors such as technological infrastructure, employee acceptance and customer requirements play an important role in implementation. However, it should be noted that these technologies can not only reduce costs, but also bring new challenges, for example in terms of theft prevention and technological maintenance [11]. Integration into omni channel strategies and overcoming barriers to acceptance by customers and employees are key factors contributing to the success of supermarkets [12]. Overall, the research shows that technological developments in retail are currently one of the most important topics shaping the current time.

Digitalization has profoundly transformed the retail sector in recent years, redefining traditional business models. Studies on the development of digital business models show that retailers are compelled to adapt their strategies by integrating modern technologies to stay competitive. Key elements of digital transformation include digitized business pro-cesses like optimized supply chains, data-driven decision-making and innovative customer interactions [13]. These digital innovations enable retailers to improve efficiency and enhance customer satisfaction. Innovation thus provides stability, as it enables companies to swiftly respond to structural changes in the market and seize emerging opportunities early on. High flexibility allows a company to act more effectively than its immediate competition and fully exploit potential opportunities [10]. The current state of research on digital innovation in retail highlights the significant role of data-driven technologies and strategic approaches in enhancing competitive advantage [14]. Longitudinal studies indicate that data-driven innovation, coupled with marketing agility, is crucial for competitive advantage in a dynamic market. Agility and adaptability are particularly advantageous in times of market turbulence, helping firms respond effectively to consumer needs [15]. By being the first to introduce innovative services, companies can achieve significant competitive edges. However, imitators can also succeed through fast-follower strategies, allowing them to avoid the pit-falls of pioneers and respond more quickly to market needs [16].

Digital and innovative transformation not only reshapes business processes but also fundamentally changes consumer behaviour. Today's customers expect seamless experiences across multiple channels, a concept known as omni channel interaction. This involves integrating physical stores, online platforms and mobile applications to create a cohesive and personalized shopping experience. Research indicates that social media and data analytics play a crucial role in crafting these tailored shopping experiences. Retailers must increasingly adapt to these digital shifts and develop innovative strategies to meet the expectations of modern consumers [17]. Digital innovations using smart technology, such as self-checkout systems, are a particularly important topic. These simplify the shopping process by reducing waiting times and replacing traditional checkouts. They are part of a comprehensive strategy for 'smart retail', which includes personalized offers via apps, real-time order tracking and contactless payment. Such technologies improve efficiency and meet the expectations of digital accessible consumers in an increasingly tech-accessible retail landscape [18]. Digital innovations are therefore not just a tool for the external image of supermarkets, but an important step towards sustainable success. Self-checkout tills are the first step in modern checkout systems.

In the context of digital tools in retail, behavioural research explores how heuristics - mental shortcuts - affect purchasing decisions. For instance, self-checkout systems might reduce the perceived waiting time, influencing customers' satisfaction and future shop-ping behaviour. However, these heuristics can also introduce biases, such as anchoring or loss aversion, which impact choices related to product selection or impulse purchases [19]. The presentation or 'framing' of options in digital interfaces, such as promotional offers displayed on self-checkout screens, can significantly alter customer preferences and behaviours [20].

Social factors also play a crucial role in retail behaviour. Concepts like fairness and reciprocity may affect how customers perceive the use of self-checkout systems compared to traditional cashier interactions [21]. For example, some shoppers might prefer human interaction for a sense of fairness or out of social habit, while others may appreciate the efficiency and privacy of digital alternatives. This social dimension influences customer acceptance and satisfaction with innovative technologies [12].

Behavioural research further examines time-related trade-offs in retail. Self-checkout and other digital innovations can reduce perceived inconvenience and waiting times, thereby enhancing the overall shopping experience [22]. However, systematic biases, such as the tendency to undervalue future outcomes, might also influence decisions like participation in loyalty programs or adoption of new digital services [12].

Overall, applying behavioural economics in the retail sector offers practical insights into how digital tools reshape customer experiences and purchasing behaviour [23]. This understanding can inform more effective implementation strategies for self-checkout systems, personalized marketing and other technological innovations, ultimately improving customer satisfaction and driving business success [24].

2.3 Retail, Digital Innovation and Customer Behaviour

Based on the theoretical insights, the following four specific research guiding questions (RQ1, RQ2, RQ3 and RQ4) were formulated to guide the empirical investigation of this study:

- RQ1: Do customers favour digital tools over traditional options when paying in supermarkets? Why or why not?
- RQ2: Does the age of the customer influence the choice of checkout when paying in supermarkets?
- RQ3: Does the number of items purchased influence the choice of checkout when paying in supermarkets?
- RQ4: How does the average waiting time at self-checkouts differ from the waiting time at conventional checkouts in supermarkets? How do the average waiting times change at peak times?

With these five research guiding questions the study addresses specific aspects that have not been fully explored in previous studies on self-checkout systems. It examines how demographic factors, such as age and familiarity with technology, influence the choice between self-checkout and traditional checkouts. Additionally, it explores the impact of purchase size on checkout preferences and assesses how important the availability of both checkout options is to customer satisfaction. By focusing on these behavioural and situational factors, the survey provides deeper insights into the adoption and integration of digital tools in retail.

3 METHODS

3.1 Customer Observations

First this study involves *observation*s aimed at capturing and interpreting *consumer* experiences in their natural context. This approach enables observers to see how consumers interact with the self-checkout service. The focus is on uncovering the interactions between various actors within the consumption ecosystem. This method complements traditional surveys by not only documenting consumer experiences but also capturing their behaviours and the influences of other actors during the consumption process [25]. The aim of the observation in this study is to investigate the average waiting times of customers at the conventional checkout and at the self-checkout. In total 200 customers are observed on the 11th of November 2024 between 1 pm and 3 pm in a supermarket in Heilbronn, Germany. The survey period is deliberately chosen on the assumption that people tend to go shopping on Mondays, as shops are closed on Sundays. This is done with 100 people at a normal time (3 pm) and 100 people at the rush hour (6 pm) when there is a very high volume of customers. Particular attention is paid to queuing time and handling time so that a total time for the process can be determined in the end. Special incidents are also noted. Stopwatches, a note log and a table for data recording are available. The observation process includes the start of the queueing time, the end of the queueing time/start of the processing time and the end of the processing time. The resulting data forms the ideal basis for analysing and comparing the two checkout types.

3.2 Customer Survey

Second a *customer survey* is conducted in the same supermarket in Heilbronn, Germany, as well on the 11th of November 2024. Before participating, customers are pre-screened based on their apparent age and willingness to take part. The survey is conducted primarily through an online questionnaire. The persons carrying out the questionnaire ask customers directly after their shopping experience, where they still have the most memories. The questionnaire is either filled out by the respondent directly or on a mobile device by a responsible person from the survey team, who enters the data of the respondents so that the customers did not have to fill in the questionnaire themselves. For participants less familiar with digital tools, for example, such as older customers, direct interviews are conducted by the survey team. To ensure efficiency and comfort, respondents are guided through the questionnaire by the survey team using a mobile device, with the survey team reading out and explaining the questions directly. A mixed-methods approach is employed for the questionnaire [26]. Open-ended questions are posed, allowing customers to share their shopping experiences through self-checkout systems. Additionally, specific questions are included to gather precise in-formation, such as the number of items customers purchased [27, 28]. Firstly, demographic questions were answered. After that, the customers are asked which type of cash register they have chosen. Depending on the answer, the questionnaire is divided into the self-checkout and conventional checkout stands. The customers describe their shopping experiences and impressions. Finally, the customers state whether the choice between the different checkout options is important to them. A total of 103 customers participate in the survey, reflecting a diverse demographic pro-file. The respondents have an average age of 43, ranging from 7-12 years to 65+ years. The gender distribution is 50,5% male, 47,6% female and 1,9% diverse. The data collected was analysed in several steps. Firstly, the questionnaires were digitally recorded and stored in a structured database. Quantitative data such as preferred checkout type, waiting times and demographic information were analysed using statistical methods to identify key trends and patterns. Qualitative responses to open-ended questions were analysed to understand common themes, opinions and suggestions for improvement. The results were analysed both numerically and graphically to make the presentation clear and understandable.

4 RESULTS

The efficiency of new technologies in supermarkets often plays an important role, as it usually determines whether these technologies will prevail in the long term. In addition to the monetary factor, throughput and time savings are usually an important object of investigation [29]. In order to be able to measure the time differences, the queuing time, the processing time and the total time of 50 people each were measured at the self-checkout checkout and at the conventional checkout in a supermarket in Heilbronn, Germany. This was carried out at a normal time (3 pm) and at rush hour (6 pm). Considering the average waiting time, customers queued for 3 minutes and 10 seconds at the conventional checkout. At the self-checkout this time is reduced to 14 seconds. During the rush hour, the observed waiting time increases by 19,47% to 3 minutes and 47 seconds at the conventional checkout and by 114,29% to 30 seconds at the self-checkout. As it can be seen (Tab. 1) the queue time at the normal checkout is significantly higher at both normal and peak times, suggesting that the self-checkout queue is significantly shorter. During rush hours, the queue times at both checkouts also increase, which can be attributed to a higher observed volume of customers.

Table 1 Waiting time (in min)

	Self-Checkout	Cash register	Change (%)
Normal Time	0:14	3:10	1257,14
Rush Hour	0:30	3:47	656,67
Change (%)	114,29	19,47	

Considering the average processing time, the results here are the other way round (Tab. 2). Here the processing time is 1 minute and 8 seconds at the conventional checkout, while it is 3 minutes and 8 seconds at the self-checkout. This picture can also be seen during rush hour. During this time, the processing time at the conventional checkout increases by 11,76% to 1 minute and 16 seconds and decreases by 6,91% to 2 minutes and 55 seconds at the self-checkout. It can be seen that the processing time of the normal checkout is 63,83% lower than that of the self-checkout during normal hours and 56,57% lower during peak hours.

Table 2 Processing time (in min)

	Self-Checkout	Cash register	Change (%)
Normal Time	3:08	1:08	–63,83
Rush Hour	2:55	1:16	–56,57
Change (%)	–6,91	–11,76	

One reason for the longer processing time at self-checkout may be that 35% of the self-checkout users surveyed said that they only use it occasionally and 9% use it rarely (Tab. 3). This suggests that many shoppers are unfamiliar with the technology and need more time to complete the process than a trained cashier at a conventional checkout.

Table 3 Frequency of self-checkout usage

How often do you use Self-Checkout?	*n*	%
Always	7	15
Often	19	41
Occasionally	16	35
Rarely	4	9
Never	0	0
Total:	46	100

If now considering the total time for the two checkout types, it can be seen (Tab. 4), that the total time for the conventional checkout is 27,72% higher than for the self-checkout during normal hours. The total time also increases during peak hours. An increase of 49,27% is measured here. Overall, therefore, it can be seen that customers need more time to complete the checkout process at the normal checkout both at normal times and during the peak hours. It can also be seen that the total time spent at normal checkouts is 18,60% longer than at peak times. At self-checkout, however, the increase is only 1,49%. This shows that, on average, shoppers lose less time during the rush hour than at the conventional checkout.

Table 4 Total time (in min)

	Self-Checkout	Cash register	Change (%)
Normal Time	3:22	4:18	27,72
Rush Hour	3:25	5:06	49,27
Change (%)	1,49	18,60	

The customer survey in the same supermarket in Heilbronn, Germany, identifies primary reasons for choosing self-checkout and highlights its practical benefits. Customers were asked about their main reasons for choosing a self-checkout. The most frequently cited factors include shorter queue (80%), faster payment process (50%) and flexibility, e.g., to scan and pack at one's own pace (approximately 40%). These features align closely with the objectives of digital tools, which aim to enhance efficiency, save time and offer a more tailored shopping experience. Self-checkout systems were most popular among younger age groups (26-35 years and 19-25 years), indicating that digital natives are more inclined to adopt innovative technologies (Fig. 1).

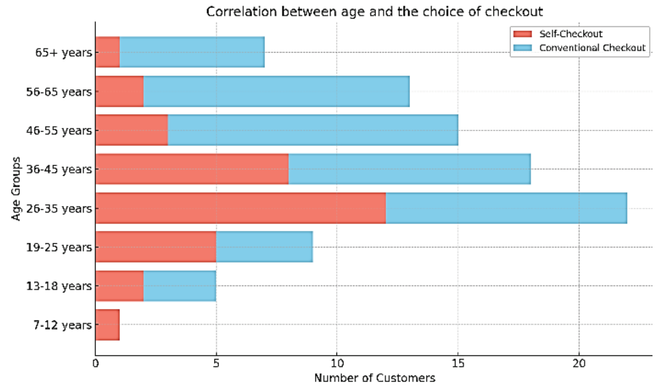

Figure 1 Connexion between age and the choice of checkout

Most respondents stated that they had chosen the conventional checkout. 46 of the 103 respondents stated that they had used the self-checkout. This means that 23,91% of respondents selected the conventional checkout. It can also be seen that the conventional checkout was chosen most often in the 26-35 age group with 24,6%, followed by the 56-65 age group with 19,3%. Self-checkout was used most frequently by the 26-35 age group with 26,1%, followed by 19-25 years with 21,7%. The result could be due to the increasing tendency towards self-checkouts among younger age groups, particularly up to the early thirties. While the older age groups from their mid-thirties to mid-sixties show a stronger preference for traditional checkouts. The age group from 26 to 35 is strongly represented in both categories, but has a higher distribution in traditional checkouts. This indicates that the choice of checkout is strongly dependent on familiarity with digital technologies and convenience preferences.

Familiarity with self-checkout systems played a key role in their usage: respondents who described themselves as "very familiar" or "rather familiar" with the technology were significantly more likely to choose self-checkout. This familiarity fosters confidence and efficiency, as experienced users can navigate the system with ease. In contrast, those who identified as "not familiar" often took more time at the self-checkout, which may explain the longer average processing times compared to traditional check-outs.

Despite the growing availability of self-checkout systems, a significant proportion of customers continue to prefer traditional checkouts; 55,3% of respondents chose this option. Several factors contribute to this preference, highlighting the enduring importance of human interaction and familiarity in the shopping experience. First, personal contact with checkout staff remains a key reason for favouring traditional checkouts. Many customers value the social interaction and the sense of support provided by trained personnel, particularly in resolving issues or ensuring a smooth payment process. Additionally, traditional checkouts are particularly favoured for larger purchases, where staff assistance in scanning and packing items significantly eases the workload for customers. Furthermore, technological familiarity plays a crucial role. Older generations or less tech-savvy individuals often perceive traditional checkouts as a simpler and more reliable option, avoiding the potential stress or errors associated with using self-checkout technology. The importance of habit is also evident, as long-standing customers often prefer the routines they are accustomed to, finding comfort in the predictability of traditional checkout systems. Lastly, the desire to avoid technical difficulties, such as malfunctioning scanners or user errors, further solidifies the preference for conventional cashiers. These systems are perceived as more efficient and problem-free, especially by those who may lack confidence in their ability to navigate digital tools effectively (Fig. 2).

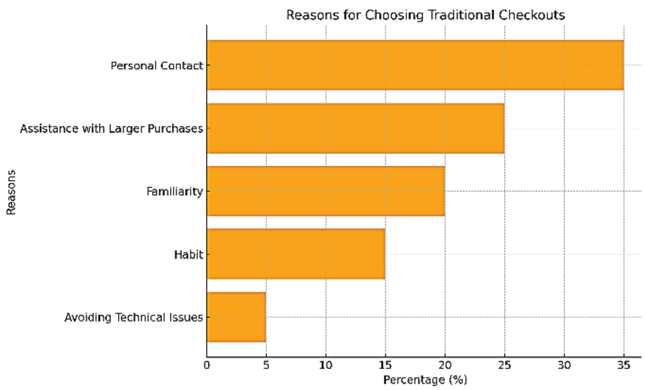

Figure 2 Reasons for choosing traditional checkouts

The data underscores the need for retailers to maintain a balance between innovative technologies and traditional services, catering to the diverse preferences and expectations of their customer base.

Next, this study looked at whether the number of items purchased had an influence on the choice of checkout. The analysis (Table 5) reveals a clear trend: as the number of items increases, the preference for conventional checkout also rises, while self-checkout is predominantly chosen for smaller purchases. For purchases of 1 to 10 items, over 80% of customers choose self-checkout. However, starting from 11 items, the preference for self-checkout decreases significantly, with conventional checkout becoming the preferred option, especially for purchases of 21 items or more (over 86%). These findings suggest that customers may be looking for personal interaction or assistance at the checkout for larger purchases, while preferring faster self-service for smaller purchases.

Table 5 Influence of the number of articles on the choice of cash register

Number of articles	Self-Checkout	Conventional checkout	Total (2 + 3)	Self-Checkout (%)	Conventional checkout (%)
1	2	3	4	5	6
1-3	5	1	6	83,33	16,67
4-10	19	4	23	82,61	17,39
11-20	17	18	35	48,57	51,43
21-50	4	25	35	13,79	86,21
>50	1	9	29	10,00	90,00
Total	46	57	103		

Then the question of whether the choice between self-checkout and conventional checkouts is important was asked. 42,7% of respondents stated that the choice was important to them. Surprisingly, less than 50% voted that the choice of checkout was important to them. People who categorise themselves as 'very familiar' or 'rather familiar' are more likely to answer 'YES' (75% or approx. 61,54%). People with lower familiarity tend to answer 'NO' significantly more often (approx. 64,29% and approx. 89,66%). A possible implication can be assumed. Familiarity seems to correlate with the assessment of the importance of the option. The more familiar someone is with self-service checkouts, the more likely it is that they consider the option to be important.

5 CONCLUSIONS
5.1 Discussion

The findings of this study reveal a picture of how digital tools, particularly self-checkout systems, influence customer purchasing behaviour in retail. While 55,3% of respondents still opted for traditional checkouts, 44,7% chose self-checkout systems. On one hand, the data high-lights the substantial advantages these innovations provide, such as shorter queue times and greater autonomy, which relates strongly with younger, tech-savvy customers. On the other hand, the longer processing times and the dependence on costumers' familiarity with the technology are obstacles for a broad acceptance (RQ1).

The findings from the survey at Edeka Heilbronn demonstrate the increasing influence of digital innovations, such as self-checkout systems, on customer behaviour and preferences. While 55,3% of respondents still opted for traditional checkouts, 44,7% chose self-checkout systems

The adoption of self-checkout systems appears to be influenced by demographic factors, such as age and familiarity with technology. (RQ2) Younger generations, often referred to as digital natives, demonstrate a higher likelihood of choosing self-checkout due to their comfort with the technology. Older customers or those less familiar with self-checkout tend to favour conventional checkouts, due to a preference for personal interaction and support. This divergence underscores the importance of addressing both generational and experiential differences when implementing such technologies.

Another notable observation is the strong connexion between the size of a purchase and checkout preference. While self-checkout systems excel in efficiency for smaller purchases, conventional checkouts remain the preferred option for larger purchases with assistance in scanning the large amount of products. This suggests that while self-checkout systems enhance convenience for quick transactions, they do not yet serve as a comprehensive replacement for conventional checkouts (RQ3).

The longer processing times at self-checkouts compared to conventional checkouts indicate a significant limitation. This discrepancy can be attributed to two factors: the learning curve associated with using new technology and the occasional need for staff intervention in cases of errors or technical issues. These challenges highlight an area where retailers must focus on improving usability and providing better support to first-time or in-frequent users. But when speaking about time, the study still showed that the total time on the self-checkouts are shorter, which is due to the fact that the queue is shorter than at the conventional checkout. From a business perspective, the data presents an opportunity for retailers to streamline their operations. While self-checkout systems offer queue time reductions, their longer processing times reduce the overall efficiency gain. Addressing these inefficiencies can unlock greater potential for these systems (RQ4).

In summary, while self-checkout systems offer significant benefits, their successful integration requires a balanced approach that addresses the diverse needs of all customer groups. By addressing these needs, retailers can maximize the efficiency and customer satisfaction of digital tools, ensuring their acceptance and long-term success in a rapidly evolving retail landscape.

5.2 Limitations and Future Research

This study has some limitations that may affect the interpretation of the results. The size amount of people participated in the survey was rather small and limited to one supermarket in Heilbronn, which limits generalisability. Future studies could include larger and more diverse samples from different locations. As the study period was limited to one day, longitudinal studies could also help to better understand seasonal and long-term changes in behaviour.

In addition to the aspects analysed, it would be interesting to investigate how the introduction of self-service checkouts affects sales and goods throughput. It could also be investigated whether the use of such technologies could replace staff in the long term and what the social and economic consequences of this would be for the retail sector. Such findings could provide valuable information for strategic planning in the sector.

5.3 Practical Implications

The results extend the understanding of the interfaces between digital innovation and consumer behaviour. There are recommendations for retailers on how to implement and optimise self-service checkouts. Targeted customer training on how to use the technology and a more intuitive design could improve adoption and efficiency. In addition, companies should strategically plan the introduction of such technologies in order to secure economic benefits and increase customer satisfaction without neglecting social factors.

Increasing technological change in retailing raises social issues, particularly in terms of potential job losses or loss of human interaction. It is important to minimise potential negative social impacts through social measures and appropriate integration of technologies into existing work structures. At the same time, such technologies offer the opportunity to improve working conditions by reducing the burden of routine tasks. And in times of shortage of skilled staff self-service checkout can be one solution for the retail sector.

6 REFERENCES

[1] EHI Retail institute GmbH (2023). *Self-Checkout: Markterhebung 2023*, https://www.self-checkout-initiative.de/markterhebung-2023/, last accessed: December 7th, 2024.

[2] VHB (Verband der Hochschullehrerinnen und Hochschullehrer für Betriebswirtschaft e.V.) (2024). *VHB Publication Media Rating 2024*, https://www.vhbonline.org/en/services/vhb-rating-2024, last accessed: December 7th, 2024.

[3] Resurchify (2024). *Ranking*, https://www.resurchify.com/ranking, last accessed: December 7th, 2024.

[4] Kraus, S. et al. (2022). Literature reviews as independent studies: guidelines for academic practice. *Review of Managerial Science, 10*(2), 2577-2595. https://doi.org/10.1007/s11846-022-00588-8

[5] Munn, Z. et al. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology, 18*(143), e0611-x. https://doi.org/10.1186/s12874-018-0611-x

[6] Eco, U. (2015). *How to write a thesis*. The MIT Press. https://doi.org/10.7551/mitpress/10029.001.0001

[7] Snyder, H. (2019). Literature review as a research methodology: An overview and guide-lines. *Journal of Business Research, 104*, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

[8] Heins, C. (2023). Artificial intelligence in retail - a systematic literature review. *Foresight, 5*(2), 264-286. https://doi.org/10.1108/FS-10-2021-0210

[9] Cai, Y.-J. & Lo, Ch. K.Y. (2020). Omni-channel management in the new retailing era: A systematic review and future research agenda. *International Journal of Production Economics, 229*, e107729. https://doi.org/10.1016/j.ijpe.2020.107729

[10] Chatzoglou, P. & Chatzoudes, D. (2018). The role of innovation in building competitive advantages: an empirical investigation. *European Journal of Innovation Management, 21*(1), 44-69. https://doi.org/10.1108/EJIM-02-2017-0015

[11] Reid, S. A., Vetter, G., Lackes, R. & Siepermann, M. (2024). Is it all about fun? Self-service technology acceptance in Germany. *The International Review of Retail, Distribution and Consumer Research, 34*(2), 201-227. https://doi.org/10.1080/09593969.2024.2342795

[12] Duarte, P., Silva, S. C., Linardi, M. A. & Novais, B. (2022). Understanding the implementation of retail self-service check-out technologies using necessary condition analysis. *International Journal of Retail & Distribution Management, 50*(13), 142-150. https://doi.org/10.1108/ijrdm-05-2022-0164

[13] Mostaghel, R., Oghazi, P., Parida, V. & Sohrabpour, V. (2022). Digitalization driven retail business model innovation: Evaluation of past and avenues for future research trends. *Journal of Business Research, 146*, 134-145. https://doi.org/10.1016/j.jbusres.2022.03.072

[14] Pattinson, St., Damij, N., El Maalouf, N., Bazi, S., Elsahn, Z., Hilliard, R. & Cunningham, J. A. (2023). Building green innovation networks for people, planet, and profit: A multi-level, multi-value approach. *Industrial Marketing Management, 115*, 408-420. https://doi.org/10.1016/j.indmarman.2023.10.016

[15] Alghamdi, O. A. & Agag, G. (2024). Competitive advantage: A longitudinal analysis of the roles of data-driven innovation capabilities, marketing agility, and market turbulence. *Journal of Retailing and Consumer Services*, 76, e103547. https://doi.org/10.1016/j.jretconser.2023.103547

[16] Bouncken, R. B., Fredrich, V., Kraus, S. & Ritala, P. (2019). Innovation alliances: Balancing value creation dynamics, competitive intensity and market overlap. *Journal of Business Research, 112*, 240-247. https://doi.org/10.1016/j.jbusres.2019.10.004

[17] Sagar, S. (2024). The Impact of Digital Transformation on Retail Management and Consumer Behavior. *IOSR Journal of Business and Management, 26*(1), 6-14. https://doi.org/10.9790/487X-2601010614

[18] Vadruccio, R., Seghezzi, A. & Tumino, A. (2024). Smart technologies for retailing: who, what, where and why,

International Journal of Retail & Distribution Management, 52(13), 79-102. https://doi.org/10.1108/IJRDM-06-2023-0408

[19] Yasseri, T. & Reher, J. (2022). Fooled by Facts: Quantifying Anchoring Bias through a Large-Scale Analysis. *Journal of Computational Social Science, 5*, 1001-1021. https://doi.org/10.1007/s42001-021-00158-0

[20] Di Crosta, A. et al. (2023). Changing Decisions: The Interaction between Framing and Decoy Effects. *Behavioral Science*s, 13(9), e755. https://doi.org/10.3390/bs13090755

[21] Ramulu, B. & Justin, P. (2023). Social influence research in consumer behavior: What we learned and what we need to learn? - A hybrid systematic literature review. *Journal of Business Research, 162*, e113870. https://doi.org/10.1016/j.jbusres.2023.113870

[22] Li et al. (2023). The Impact of the Macroeconomic Environment on Social Preferences: Evidence from the Global Preference Survey. *Behavioral Sciences, 13*(8), e648. https://doi.org/10.3390/bs13080648

[23] Leigh, A. (2015). How behavioral economics does and can shape public policy. *Economic and Labour Relations Review, 26*(2), 339-346. https://doi.org/10.1177/1035304615579346

[24] Grewal, D., Roggeveen, A. L. & Nordfält, J. (2017). The Future of Retailing. *Journal of Retailing, 93*(1), 1-6. https://doi.org/10.1016/j.jretai.2016.12.008

[25] Becker, L. (2018). Methodological proposals for the study of consumer experience. *Qualitative Market Research, 21*(4), 465-490. https://doi.org/10.1108/QMR-01-2017-0036

[26] Flick, U. (2023). *An Introduction to Qualitative Research*. Sage, London, https://us.sagepub.com/en-us/nam/an-introduction-to-qualitative-research/book278983

[27] Krosnick, J. & Presser, S. (2010). Question and Questionnaire Design, Marsden, P. V. & Wright, J. D. (Eds.). *Handbook of Survey Research*. Emerald, Bingley, 264-313. https://bookstore.emerald.com/handbook-of-survey-research-hb.html

[28] Callegaro, M., Manfreda, K. L. & Vehovar, V. (2015). *Web survey methodology*. Sage, Thousand Oaks. https://doi.org/10.4135/9781529799651

[29] Quinones, M.; Gomez-Suarez, M.; Cruz-Roche, I.; Díaz-Martín, A. M. (2023). Technology: a strategic imperative for successful retailers. *International Journal of Retail & Distribution Management, 51*(4), 546-566. https://doi.org/10.1108/IJRDM-03-2022-0088

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Application of AI-based Predictive Maintenance for Industrial Processes

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Abstract: Modern industry is increasingly relying on digital technologies to optimize maintenance processes, reduce costs and ultimately increase productivity. Conventional maintenance models, such as corrective and preventive maintenance, often lead to unnecessary downtime and high operating costs. Predictive Maintenance (PdM), which is based on data analysis and artificial intelligence (AI), enables the timely detection of failures and the optimization of maintenance cycles and is therefore a key component of modern industry. With the advancement of artificial intelligence (AI) and machine learning, data analytics can accurately predict failures, thereby reducing the need for preventive and corrective maintenance in the form that was common before the application of AI. Predictive maintenance (PdM) is emerging as a key element of modern industry, enabling a significant reduction in downtime, an increase in operational efficiency and a reduction in maintenance costs. This paper explores the application of artificial intelligence, including machine learning (ML), deep learning (DL) and the Internet of Things (IoT) in predictive industrial maintenance, analyzes the key implementation challenges in implementation, considers the potential benefits for industrial systems and discusses the challenges and prospects for the further development of this approach.

Keywords: Artificial Intelligence (AI); Deep Learning (DL); Internet of Things (IoT); Machine Learning (ML); Predictive Maintenance (PdM)

1 INTRODUCTION

In the course of industrial development, the maintenance of industrial plants has evolved from reactive to preventive maintenance. Due to the strong development of digitalization and Industry 4.0, predictive maintenance is becoming the industry standard for efficient maintenance. The development and thus the application of artificial intelligence (AI), machine learning (ML) and database analytics such as failure history enables the prediction of failures before they occur from a different perspective, which ultimately reduces costs and increases the availability of production facilities [1]. Industrial production itself relies on the continuous functionality of machines and systems to ensure higher productivity and profitability.

However, breakdowns and unplanned downtime often pose a major problem to the ambitious targets, especially those of high mechanical availability, often above 95%, which ultimately causes significant financial losses and affects the availability and reliability of production processes. According to certain studies, unplanned downtime in industry can cause billions of dollars in losses every year, and no less than 82% of companies have experienced sudden, unplanned downtime in recent years [1].

Conventional approaches to maintenance models, such as reactive and preventive, have significant shortcomings. With reactive maintenance, maintenance measures are only carried out when a failure occurs, while preventive maintenance often includes maintenance measures that are not necessary, which ultimately increases maintenance costs, i.e. overall production costs. Accordingly, there is a growing need for smarter and more efficient maintenance strategies that can minimize these problems and thus contribute to various benefits of maintenance. Predictive maintenance (PdM) uses sensor input data for the necessary analysis, including Internet of Things (IoT) and AI algorithms, as well as Fuzzy Logic, Genetic Algorithms, which would actually have the function of predicting potential failures before they occur. Such activities are very important from the perspective of predictive maintenance itself, before a failure, breakdown or major downtime of the production process occurs. By implementing artificial intelligence models into the maintenance function, such as deep neural networks (DNN), multi-channels deep convolutional neural network (MC-DCNN), artificial neural network (ANN), convolutional neural networks (CNN) and recurrent neural networks (RNN), PdM provides the ability to estimate the probability of failure and influences the optimization of maintenance management. With the accelerated development of Industry 4.0 technology, predictive maintenance is becoming a fundamental tool for improving industrial processes, with a significant increase in mechanical availability and reliability. This paper provides an insight into the applications of AI in PdM, examines existing methods, presents the current challenges of modern industry and highlights future directions for the development of these technologies.

2 A BRIEF OVERVIEW OF THE EVOLUTION OF MAINTENANCE

The evolution of maintenance in industry can be divided into several broad key phases that have accompanied the development of industry itself, from reactive maintenance to predictive and smart maintenance, which is still used in industry today. In order to better understand the development of the maintenance process, a brief historical overview of the development of maintenance in industry is provided:

1) **Reactive maintenance (before 1900)**

Main feature: Repair after failure

Maintenance was most often conceived of as repair after a failure occurred. There was no basic systematic approach, but the production workers carried out the maintenance activities after a failure occurred. All production in terms of maintenance took place in the uncertainty of failure because the condition of the equipment and the risks of failure were unknown.

Example: Early machinery in the textile and mining industries, as mentioned, was only repaired when a failure occurred.

2) Preventive maintenance (1900)

Key feature: Scheduled inspections and replacement before failure occurs

With the development of industrialization and mass production (especially after the introduction of the assembly line in Ford factories), the importance of taking various measures to regularly inspect and replace parts that are worn out but have not yet been used up was recognized. Due to the technology that was in use at the time, this type of maintenance was not effective.

Example: Preventive maintenance measures are introduced in the aviation and automotive industries to reduce the number of breakdowns

3) Proactive maintenance (1950)

Key feature: Identification of the cause of failure of strategically important equipment

The development and application of risk and maintenance management methods, such as root cause analysis (RCA) and total productive maintenance (TPM), are slowly finding their way into effective failure management, i.e. effective maintenance management.

The goal of these tools is the timely detection of the causes of equipment failures that cause significant losses and to increase the reliability of production processes.

Example: Japanese factories use TPM in the automotive industry to increase production efficiency and reduce maintenance losses.

4) Predictive maintenance (1980)

Main feature: Use of sensors and data analysis in "offline" and "online" methods

Technological development of equipment and digitalization enable the use of various sensors, thermal imaging, ultrasound and vibration analysis to predict the condition of equipment, ultimately giving insight into the state of faults before they occur.

Example: Various manufacturing processes, process industries use vibration recording to perform analysis to detect irregularities in the exploitation of machinery.

5) Smart maintenance (2010)

Key feature: Artificial intelligence and IoT in modern industry

The application of Internet of Things (IoT) tools, machine learning and big data enables automated decisions in real time, which has an impact on predictive maintenance. Such approaches increase the reliability and mechanical availability of industrial processes.

Example: Industry 4.0 uses digital twins and AI algorithms to optimise machine maintenance in order to increase efficiency.

Maintenance approaches have evolved from simple repairs after a failure occurs to sophisticated systems that predict and prevent failures before they occur, increasing the reliability of production processes and reducing the costs caused by faults and breakdowns.

In summary, it can be concluded that maintenance strategies have developed in three main phases since the beginning of industrialization:

- **Reactive maintenance:** repairing equipment after a failure has occurred. This type of approach is very inefficient and often leads to long downtimes and high costs due to the need for quick maintenance and the procurement of spare parts [2].
- **Preventive maintenance:** Includes planned activities to check the condition of equipment and replace equipment parts at planned intervals. Although it improves reliability, it often results in unnecessary replacement of correct components that may still be in use, increasing operational maintenance costs [3].
- **Predictive Maintenance (PdM):** Uses AI technology and analysis of data collected from production processes to detect early signs of failure before a breakdown occurs, and ultimately optimizes maintenance based on the actual condition of the equipment [4].

The evolution of maintenance in the industry shows a clear path of industrial development from a simple, reactive approach to more advanced, sophisticated methods that enable greater reliability and efficiency in the production of process equipment. From post-failure repairs, through preventive and proactive methods, to the use of advanced sensors and data analytics, the industry is constantly evolving to reduce costs, increase productivity and manage and reduce unplanned downtime in production processes. This maintenance approach enables better control over the maintenance of production processes and lays the foundation for the further development of smart and autonomous maintenance systems in the future.

3 COMPARISON OF PREVENTIVE (PM) VS. PREDICTIVE MAINTENANCE (PdM)

The maintenance of industrial plants, especially complex plants such as those in the process industry, is usually based on various strategies to ensure their reliability, availability, safety and ultimately their cost-effectiveness. In most cases, the maintenance strategy defines two main approaches to maintenance, namely preventive and predictive maintenance. The maintenance strategy itself is not designed with just one maintenance approach due to the different types of systems and the varying complexity of the equipment.

3.1 Preventive Maintenance

The brief description of preventive maintenance (PM) already given actually implies the implementation of pre-planned, defined maintenance activities with the aim of preventing failures and reducing the frequency of unforeseen downtime. The activities listed include a series of planned maintenance actions in order to successfully perform maintenance, such as regular inspections of equipment, lubrication of equipment, replacement of parts and calibration of equipment, and are based on predefined time intervals or on the mean time between failures (MTBF) defined by the failure distribution. The overall preventive maintenance plans are defined by the maintainer, who uses various assessment tools such as risk matrices, failure distributions, failure history and the like.

Preventive maintenance can generally be divided into three parts for better perception:

Constant interval maintenance – is based on predefined time intervals, such as operating hours, and does not take into account the actual condition of the equipment. The logic of this approach is based on the assumption that an equipment or process component is expected to fail or malfunction after a certain period or hours of operation. Such defined maintenance measures are carried out before a failure occurs.

Age-dependent maintenance – equipment maintenance activities are carried out after a component has reached a certain age or a certain number of operating hours. This approach assumes that failures become more likely as the equipment ages or as operation progresses, which is the actual and expected sequence of maintenance. Therefore, certain equipment is replaced and repaired before a fault or failure occurs.

Imperfect maintenance – is a form of maintenance that usually does not always restore the system to its original state in a completely new state, but partially improves the condition of the component or system, i.e. its functionality and reliability. It can also be said that with this form of maintenance, the system is not at the full reliability level of the equipment, i.e. the component, but is in an intermediate state between failure and the state of full reliability. It should be noted that, according to the definition of imperfect maintenance, it is not possible to restore the original reliability in the service process – all maintenance is therefore imperfect. This method often leads to high maintenance costs and is not relevant for further processing when assessing the risk status, as it does not take into account the actual condition of the equipment.

3.2 Predictive Maintenance

Predictive maintenance (PdM) is certainly a more sophisticated concept, based on the continuous monitoring of the condition of the equipment using various diagnostic tools and techniques. Some of these are vibration analysis, thermography, oil analysis, ultrasonic testing and others. The main objective of such an approach is to predict faults that are present in the equipment and process but are not yet visible during operational use of the equipment. After identifying such faults in the early stages of their occurrence, corrective maintenance actions can be planned before the failure occurs.

Predictive maintenance can generally be divided into several parts:

Condition-Based Maintenance (CBM) – the continuous monitoring of key parameters or key equipment - helps to enable decisions based on the actual condition of the equipment or the system that ultimately constitutes the equipment. The main feature of this type of maintenance is that maintenance actions are only carried out when signs of system anomalies occur, rather than according to predefined time intervals as in preventive maintenance. The aim of this type of maintenance is to continuously monitor the actual condition of the equipment and only carry out maintenance measures when necessary. This maintenance approach optimizes costs and reduces unnecessary activities to replace parts that are still working.

Reliability Centered Maintenance (RCM) – a maintenance concept that focuses on the reliability of equipment by analyzing potential failures and their impact on the entire system. The most important steps in implementing this type of maintenance are identifying the function of the equipment, which includes defining the primary and secondary functions that this equipment must perform; next, recognizing the type of failure of the equipment, which is the function of analyzing how the equipment cannot perform the defined functions; next, determining the cause of the failure to identify the reason for the failure in depth; while the next step considers the evaluation of the consequences of the failure, e.g. on safety, environment, operating costs; while the last step is perhaps the most important because it defines the selection of a maintenance strategy based on the previous steps. The last step in the RCM is crucial as it determines for which equipment a maintenance strategy is defined; it classifies the equipment and assigns it the appropriate maintenance strategy, corrective, preventive, predictive or mixed strategies, strategy by reliability etc.

The main advantage of predictive maintenance over preventive maintenance ultimately lies in reducing the number of maintenance interventions, extending equipment life, knowing the condition of the equipment, achieving significant maintenance savings and increasing reliability and mechanical availability.

Preventive maintenance, as traditionally applied in maintenance management, comes up against certain limits when it comes to optimizing costs and resources. While predictive maintenance reduces downtime and increases availability, reliability and safety by making more efficient use of production facilities.

As modern industrial equipment requires significant mechanical availability, often exceeding 95%, which ultimately leads to higher reliability and has a direct impact on the reduction of operational potential that is not transformed into production impact, predictive maintenance becomes a dominant strategy over other applicable strategies in many manufacturing sectors as it offers various benefits, including a significant reduction in operating costs.

4 THE ROLE OF ARTIFICIAL INTELLIGENCE IN PREDICTIVE MAINTENANCE

Artificial intelligence and machine learning (ML) enable high-precision monitoring of equipment condition parameters and early detection of potential faults that actually indicate future failures based on the analysis of collected data, such as vibration records. The most important AI methods in maintenance include:

- **Machine learning (ML):** includes algorithms such as regression, classification and neural networks which analyze failure history and real-world data and detect early patterns that indicate the occurrence of failures [5].

- **Anomaly detection:** AI models analyze deviations from defined upper and lower limits in machine operation and signal potential failures before failures occur [6].
- **Remaining Useful Life (RUL) estimation:** Various AI models, especially with deep neural networks, enable a realistic estimate of how long a particular component will continue to function before maintenance is required or a failure occurs [7].

The application of artificial intelligence and machine learning significantly improves the efficiency of plant maintenance by enabling condition monitoring and prediction of failures. With the help of data analysis algorithms, AI systems detect defined deviations, predict the service life of components and enable timely interventions before a fault or failure occurs. Deep neural networks (DNN) and recurrent neural networks (RNN) have proven to be very effective in predicting failures and optimizing maintenance [8]. The application of AI models in predictive maintenance enables rapid identification of potential problems and optimization of priorities when performing maintenance in real time. This approach not only reduces costs and unplanned downtime, but also increases the reliability and productivity of industrial plants, making maintenance more proactive and intelligent.

5 INTEGRATING PREDICTIVE MAINTENANCE WITH INDUSTRY 4.0

The development of Industry 4.0 technologies enables new possibilities in the field of predictive maintenance, enabling more accurate and efficient analysis of industrial processes. Modern technologies such as the Internet of Things (IoT), 5G networks and digital twins enable the collection and processing of large amounts of data in real time, increasing the ability to predict potential failures and optimize the maintenance of production processes. The integration of these technologies with artificial intelligence and data analysis further increases the reliability and efficiency of industrial processes. Industry 4.0 technologies such as the Internet of Things (IoT), 5G networks and digital twins further enhance predictive maintenance as follows:

- IoT sensors enable the collection of various data, for example on temperature, vibrations and pressure, which serve as input data for AI algorithms based on which analyzes will be performed [8].
- 5G communication ensures fast data transmission in real time and enables faster response and processing of the data so that the information gains its true meaning [9].
- Digital Twins use real-time data to simulate the operation of industrial systems and predict future problems that can be eliminated in a timely manner [10].

The integration of predictive maintenance with Industry 4.0 technologies enables a positive transformation of traditional maintenance approaches into intelligent and automated systems that can respond in real time, bringing many benefits. By using IoT sensors for data collection, 5G networks for fast information transfer and digital twins for simulating and analyzing plant operations, the industry has the prerequisites for achieving greater efficiency and reducing unplanned downtime. This combination of technologies provides new possibilities for preventive maintenance, especially predictive maintenance, which we can freely call new generation maintenance, adapted to the requirements of modern production and modern industrial facilities.

6 ADVANTAGES AND CHALLENGES OF APPLYING AI IN PREDICTIVE MAINTENANCE OF INDUSTRIAL PLANTS

Maintenance using AI in PdM brings significant benefits, such as reduced downtime, lower maintenance costs and greater safety for production workers. It is certainly important to note the challenges that manufacturing faces when using such technologies, such as the need for high quality data, the complexity of implementation and the need for skilled labor [11].

Some of the benefits highlighted would be: reduced production equipment downtime and operational maintenance costs, increased worker safety, optimization of consumption of available resources, automated decision making based on quantitative data, significantly extended equipment lifespan with reduced cost of replacing consumable parts, while some of the challenges would be the following: integrating AI systems into existing industrial infrastructure, ensuring high quality data for analysis, lack of skilled professionals who can handle AI technologies, security challenges related to digitalization and cyber-attacks on industrial facilities that we are unfortunately experiencing [10].

The application of AI in industry can provide maintenance management staff with the equivalent of an experienced maintenance expert who continuously analyzes all the data collected from the equipment in operation, such as temperature, vibration records, torque, speed and other indicators of the condition of the equipment in operation. In this way, AI can predict and detect various deviations, warn employees in a timely manner and even provide useful insights based on the history of equipment failures using certain analytics.

The perception of the application of AI in maintenance can sometimes be confusing for employees, and after training, it contributes significantly to making informed assessments based on solid “tangible” evidence, and thus to the acceptance of AI “maintenance” employees. Artificial intelligence in predictive analytics transforms 'raw' data into actionable information on which appropriate maintenance decisions are made, usually in real time, before a failure occurs. For example, by analyzing equipment failures in the history of failures, a predictive model can predict future failure patterns, such as failure distribution and the like, which contributes to significant benefits.

7 CONCLUSION

The application of artificial intelligence (AI) in predictive maintenance brings significant benefits to industrial maintenance systems by enabling a reduction in operational maintenance costs, increasing the productivity of production processes and reducing unplanned downtime, which also impacts the bottom line. By using advanced machine learning algorithms, real-time sensor data and Industry 4.0 technologies, predictive maintenance enables accurate analysis of equipment condition and timely action before failures occur.

The application of the Internet of Things (IoT), 5G networks and digital twins in production processes improves the ability to predict and optimize maintenance itself, increasing the reliability of production systems. The advantages are many, but there are also challenges such as the need for high-quality data, the complexity of the implementation itself and the lack of qualified experts, which are often obstacles that must be overcome in order to fully exploit the potential of this technology.

The future of AI in maintenance probably lies in the further development of AI and IoT technologies, with PdM becoming even better, more precise, faster and smarter. The application of generative artificial intelligence (GAI) will enable deeper and more complex data analysis, while quantum computing will significantly accelerate analytical processes and predictions in maintenance. In predictive maintenance, the basis is to obtain data as soon as possible after the occurrence of anomalies and take corrective action before a malfunction occurs, while the future will certainly lie in autonomous robotic systems that perform inspection and repair activities independently, thus reducing the need for human intervention. It can therefore be concluded that AI is not just a tool for improving maintenance, but will shape the future of industrial production and enable fully automated, intelligent management of machines and available resources.

The advancement of artificial intelligence and digital technologies provides the opportunity to further automate and optimize the maintenance of production facilities, making the industry even more efficient, safe and resilient to unpredictable failures. Predictive maintenance based on artificial intelligence is becoming a key tool for modernizing industrial processes and ensuring sustainability and competitiveness in a dynamic industrial environment.

8 REFERENCES

[1] Nadaf, A. (2024). AI-Based Predictive Maintenance in Industry 4.0. *Journal of Industrial Technology, 58*(3), 145-163.

[2] Jovancic, D., Markovic, P., & Radosavljevic, J. (2022). Comparative Study of Maintenance Strategies in Smart Manufacturing. *IEEE Transactions on Industrial Informatics, 18*(7), 3298-3312.

[3] Mohan, R., Patel, V., & Singh, A. (2023). Machine Learning Approaches for Predictive Maintenance in Manufacturing Systems. *Elsevier Robotics & Automation Journal, 12*(5), 1023-1045.

[4] Pérez, M., Torres, J., & Gómez, C. (2021). Integration of IoT and AI for Predictive Maintenance in Automotive Industry. *Springer Advances in Intelligent Systems, 27*(4), 267-289.

[5] Khaled, M. (2023). Deep Learning Applications in Predictive Maintenance: A Review. *ACM Journal of AI Research, 15*(2), 312-334.

[6] Poór, P., & Basl, J. (2019). Predictive Maintenance as a Tool for Reducing Operational Costs in Industry 4.0. *International Journal of Production Research, 57*(6), 1743-1761.

[7] Zonta, T., da Silva, M. M., & Barbosa, J. (2022). Neural Networks for Predicting Remaining Useful Life of Industrial Components. *IEEE Transactions on Neural Networks, 29*(5), 885-902.

[8] Gama, L., Ferreira, R., & Santos, H. (2022). IoT-Enabled Predictive Maintenance: Advances and Challenges. *Elsevier Internet of Things Journal, 14*(3), 567-589.

[9] Zhang, W., Li, X., & Wu, J. (2023). 5G-Driven Predictive Maintenance: A Case Study in Smart Factories. *Springer Smart Manufacturing Review, 21*(4), 112-127.

[10] Müller, K., Hoffmann, B., & Schneider, T. (2021). Digital Twins for Industrial Predictive Maintenance: A Systematic Review. *IEEE Internet of Things Journal, 8*(9), 4545-4563.

[11] Smith, R., & Johnson, P. (2022). Challenges and Future Directions in AI-Based Predictive Maintenance. *Journal of Industrial AI, 19*(7), 102-121.

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The Insights into the Implementation and Interdependence of AI and Technological Humanism in Manufacturing Companies

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Abstract: Manufacturing companies are gaining advantages through the introduction of new technologies, but problems related to human resources, management, and organization have been identified. Industry 5.0 represents a new concept whose goal is to enable the synergy of people and machines. Its part concerning technological humanism is gaining more and more importance due to the very rapid development of new technologies, and it is especially important when considering the application of Artificial Intelligence in companies and the related consequences for the organization and employees. As Artificial Intelligence represents systems capable of performing complex tasks that historically only a human could do, it's influence on human workers is very significant and therefore there is a need for deeper research and understanding. The conducted empirical research provides a technological-humanistic insight related to the implementation of artificial intelligence that companies should consider in order to enable successful collaboration between man and machine.

Keywords: artificial intelligence; manufacturing companies; technological humanism

1 INTRODUCTION

Global business today is faced with major and turbulent changes, and manufacturing companies, due to the specific nature of their business, are exposed to numerous challenges. As a result, the manufacturing sector has the need to improve its existing activities in terms of increasing adaptability and flexibility, in order to meet the changing needs of its customers and the corresponding market. [1]. Therefore, organizations must commit to implementing a series of organizational changes in order to improve their business, most of which are related to the implementation of new technology. Digital transformation in the manufacturing industry has recently shown increasingly intensive development, and with its technological innovations, it enables its development and a consequent future supported by artificial intelligence, human-robot collaboration, smart solutions, automated production, with changed qualification requirements, completely new job profiles, but also potential job losses. [2].

Artificial Intelligence (AI) represents an important part of Industry 5.0. In its strictest definition, AI stands for the imitation by computers of the intelligence inherent in humans [3], referring to the simulation of human intelligence by a system or a machine, with the goal to develop a machine that can think like humans and mimic human behaviours, including perceiving, reasoning, learning, planning, and predicting [4]. As its integration in the workplace creates many challenges and opportunities [5], considering its influence on human workers is very important for the company at present, and will be even greater in the future. Therefore, there is a need for deeper research and understanding of the involvement of AI in the operations of companies and the entire business system, taking into account its rapid development and its aspects, including interaction with people and its consequences. Manufacturing companies represent very sensitive organizations because many of them are still oriented towards traditional production processes, routines and corresponding organisation, even after implementing digital solutions. AI could provide compounding benefits to the manufacturing industry, but at the same time, the AI solutions also require a thorough understanding of the possible trade-offs involved and the specific needs and capabilities of the company and stakeholders [6].

Technological humanism views technology in the service of humans and recognizes that automation, due to the adoption of digital technologies, is able to encourage instantaneous and delocalized activities thereby increasing flexibility and dynamism, but at the cost of a greater amount of insecurity and uncertainty in the work system [7]. With regard to the implementation of technology and its possible consequences, the concept of technological humanism encourages the preservation of the ethical centrality and primacy of humans in automated environments [8]. This concept incorporated into businesses considers not only how new technologies, tools, and methods will enable better business results, but also how these factors can influence the creation of a more humane and sustainable business environment [9]. Besides focusing only on automation and optimization, it considers the aspect of participation of involved people with the aim of increasing human capabilities [10] and in the production environment it observes technology with the aim of encouraging human development with social integration, in enterprises that have the purpose of achieving joint action of all social subjects in the creation of shared values [11].

As AI increasingly becomes a standard component of production processes [12] and represents an important part of ever-widening digitalization, in these conditions it is crucial to discuss humanism, which is important for the people involved [10]. By implementing technological humanism companies are able to remove possible obstacles from the internal environment related to the human factor, which have been identified as more significant than extrinsic barriers in terms of impact in the digitalisation process [13]. This can then be positive for establishing an appropriate organizational culture and factors that influence the management and development of the necessary skills and expertise of employees.

2 ARTIFICIAL INTELLIGENCE (AI) AND TECHNOLOGICAL HUMANISM

In present time, AI is being increasingly adopted in manufacturing, leading to work design, responsibilities, and dynamics changes [14] and it is considered distinct from digitization and integration of information technology [6]. It can increase the productivity of the entire enterprise and the human worker [12], while at the same time its involvement in complex socio-technical environments such as production systems changes the role of the operator and his duties and responsibilities at the workplace [5]. AI enables manufacturing companies to gather and analyse copious amounts of data, identify patterns and insights, and automate processes, enabling faster and more informed decisions that improve operations and product development [6], from being only supportive, to taking decisions and action autonomously. Since the industrial environment will be redefined by the synthesis of AI and human skills, it is crucial to empirically analyse this evolutionary path [12]. Also, it is of great importance to include all individual goals of successful AI implementation in the company's comprehensive production and business system, taking into account aspects of this new technology and social factors [15]. The above is marked by certain problems that are noticeable in the present, and due to the extremely fast development of AI, they need to be solved in order to avoid their repetition and multiplication in the future. AI has been demonstrated to have a "black box" syndrome, owing to absence of insights into how systems operate, prompting several negative implications [16]. In addition, human users are reluctant to adopt techniques that are not directly interpretable, tractable, and trustworthy [17].

Since it has been identified that business organizations need to consider not only how new technologies will enable better results for their business, but also how they can influence the creation of a more sustainable environment focused on human needs [9], in this sense, the implementation of digital transformation in companies should be part of a joint effort to transform the way of doing business by integrating digital technologies so that actors directly and indirectly cooperate on a common understanding of all aspects of new technologies within and outside their business organizations [18]. The corresponding approach should be human-cantered and must meet both industrial and human needs [19]. This approach represents the concept of technological humanism, which enables the synergy of man and machine, and represents one of the most important new trends in the world of work [8]. It is based on the view that the implementation of new technologies must guarantee human beings the ability to preserve dignity and moral autonomy within automated globalization [7], and on the foundations of digital humanism which represents an ethics for the digital age that interprets and shapes the process of digital transformation in accordance with the core concepts of humanist philosophy and practice, which then encourages the development of human-centred innovations [10]. Since understanding socio-technical systems requires an equal consideration of all three factors in the form of business, technology and people in terms of responsibility for the successful implementation of digital transformation [20], within the concept of technological humanism, the need to introduce the role of a smart operator is recognized and fulfilled in terms of a paradigm shift from the simple implementation of automated and independent activities towards a human-oriented cyber-physical system [21]. In it, the employee as an operator must benefit from technologies that do not hinder him, but rather enable his development and lead him to perform each action with confidence without mental or physical stress or uncertainty [21]. Accordingly, technological humanism strives to improve the quality of human interaction with digital solutions in a dynamic environment and complex industrial systems [22]. In this area, it is recognized that technology has not yet sufficiently supported the transformation towards a globally sustainable society by providing tools that are aligned with the logic of pan-humanism, anthropo-relational humanism and digital humanism in all social and business relationships [23].

In the case of implementation and use of AI solutions in the business of production organizations, the goal is to enable successful relationship between man and machine, respecting the criterion that technology is at the service of man and his development, well-being and fulfilment, which is contained in the concept of technological humanism. In this way, its fundamental premises can be fulfilled in terms of ensuring the leadership and centrality of the human being within automated environments, as well as protecting human freedoms and eradicating inequalities and gaps associated with the exponential development of technology [8]. The reality is that workplaces are reshaped as a result of the use of AI in production, encouraging the need to develop an approach to successful collaboration between man and machine [14], and to conduct research related to the AI aspect of such enterprise transformation while respecting the norms of technological humanism.

3 RESEARCH OF THE DEGREE OF USE OF ARTIFICIAL INTELLIGENCE (AI) IN RELATION TO THE DEGREE OF IMPLEMENTATION OF TECHNOLOGICAL HUMANISM IN THE COMPANY

The reason for the present research was the results of previous case studies, conducted on a sample of two small Croatian manufacturing companies. The first case study was conducted to determine the level of employee awareness and knowledge about Industry 5.0 and consequences of its implementation on the company and on them personally in line with the concept of technological humanism according to the newly developed model. The concept of technological humanism was presented through its five components that constituted a research model [24], as shown in Fig. 1.

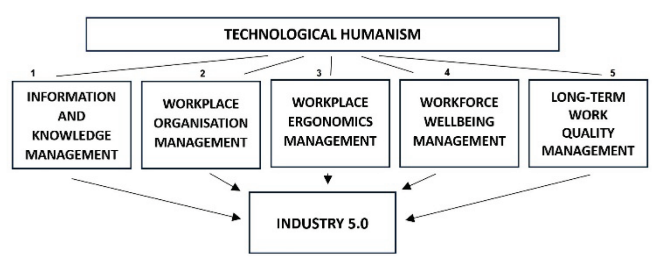

Figure 1 Graphic representation of the technological humanism model [24]

The results of this first case study showed that there was a statistically significant difference in the answers regarding the survey respondents work category in the case of model components 2, 3 and 4, as top management showed significantly difference perceptions in relations to categories of operational non-production and production workers [24].

The second case study focused on the technological-humanistic aspect of using robotic systems and AI in production, organization, and management depending on the employee's job position in the company, on a sample of the same two companies and using the same model of technological humanism as in the first case study. The case study results did not indicate statistically significant differences between work positions within the aspects of the application of robotics and using AI in production, organization and management in relation to the principles of technological humanism, but the results revealed a trend that indicates a possible difference in the perception of AI technology use and its consequences by top management compared to other categories of employees [25].

The aforementioned findings and the call to conduct new research in this area on a larger sample, including larger companies, resulted in the implementation of a new research. It aimed to investigate whether there is a statistically significant relationship between the degree of use of AI in the company's operations, and the level of implementation of technological humanism in the organization, and through the obtained results to gain information into the way these companies are organized and the associated management in the conditions of implemented AI technology, considering the fulfilment of the humanistic settings included in the concept of technological humanism. The basis of the approach for this research was the newly developed technological humanism model from the previous literature [24]. The novelty in the approach of this research is the modification of that model in the way of combining its separate components that consider workplace organization and ergonomics management into one. This was done for the reason that it is expected that although today's companies might have separate departments that deal with workplace organization and ergonomics, they would need to be united within the concern that workplace positions are organized and processes are aligned with aspects of technological change in accordance with the required ergonomics of the workplace.

The surveyed domains followed the adapted technological humanism model components (1-4):

1) **Training and education of human resources in the application of new technologies**

It is considered that the importance of soft skills and specific abilities of human resources within the process of digital transformation emphasizes the importance of including knowledge about new technologies in the routine practice of the organization [26], so effective business requires the establishment of a learning organization, which continuously changes and improves using lessons from experience [27]. It has been recognized that modelling the knowledge and expertise of workers is one of the main challenges of digital transformation [19], so in addition to a well-supported knowledge management system, it is also important to increase the involvement of employees in creating new organizational culture and ensure transparent communication in the organization [28].

2) **Organization of workplace and ergonomics in accordance with the implementation of new technologies**

The adoption of advanced technologies requires significant worker effort [29] and results in the demanding task of implementing appropriate organizational ergonomics. The specific consequences of digitalisation on people can concern both physiological and psychological areas and possible disturbances. Related disorders are described as Cyber-syndrome, which appears in conditions of frequent human interactions with cyberspace, and as a result, a new direction in ergonomics has been established – Cybergonomics [30].

3) **Use of procedures and processes to achieve employee satisfaction in changing working conditions**

The employee as an operator must benefit from technologies that do not hinder him, but rather enable his development and lead him to perform each action with confidence without mental or physical stress or insecurity [21]. Accordingly, it is necessary to establish an organization that positions the employee as an operator in a digital environment as a controller of production systems where the well-being of workers is a high priority, in such a way that he strategically uses technology to improve the quality of the working environment [22]. For this reason, a system should be established within the company to review and consider employee satisfaction in changing working conditions before negative consequences occur.

4) **Implemented system for long-term management of the quality of work of employed human resources**

Technology has affected almost all organizations in terms of changes in processes, procedures, and management, so organizations today are looking for technology-oriented employees for their operations at all levels [31]. These new conditions also establish new rules and approaches to people's work [32] and the implementation of smart manufacturing creates a challenging work environment for employees in a way that results in new types of situations and contexts of their workplaces [33]. In such circumstances, employees must be able to understand complex situations, find innovative solutions, and adapt to a constantly changing environment. [34]. In order to ensure quality in the company's work in the long term, it is necessary to establish a system that, on the one hand, ensures continuous training and development of employees, which is a key stage in ensuring the future quality of the workforce [35], and acquires new ones with a high level of necessary competencies, while on the other hand, includes the necessity of replacing workers who do not meet the required conditions [24].

From a random selection of contacted manufacturing companies, fifteen of them agreed to participate in the research. The research was conducted on companies that are all privately owned, and they were small, medium and large enterprises with annual revenues ranging from EUR 2,5 to 201 million, with the number of employees ranging from 21 to 955. The companies covered several branches of industry and included the processing of wood and wood products, the production of metal, rubber and plastic products, electrical equipment, paper and paper products, and the production of food products and beverages. The respondents were members of top management as individuals responsible for decision-making and management of the company. They were asked to answer questions on the one hand indicating the degree of the use of AI systems in the company they manage, and on the other hand to give an assessment of the degree of implementation of each of four components of technological humanism in their organization. The questionnaire was based on a five-point Likert scale. Before completing the questionnaire, members of top management were informed about the purpose of the research and the necessary focus on evaluating the degree of application of AI systems in their business related to production, i.e. related processes and activities. In order to avoid the possibility that respondents have their own interpretations regarding AI use, which than can influence their answers and limit the potential of reasoning based on the gained data, they were informed with AI solutions for manufacturing companies ranging from being only supportive, to making decisions and action autonomously. Accordingly, they responded in a way to assess the degree of application of AI technology in their organizations in relation to the current real situation in production. Within the part of the questionnaire that related to technological humanism, according to the presented model, it contained one question for each of its components that described its essence.

Based on the results of each component of the applied model of technological humanism, an additional variable was derived in the form of the results of technological humanism, as their arithmetic mean. Tab. 1 provides an overview of the results of descriptive statistics relating to the relationship between the use of AI systems in the company and components of the adapted research model of technological humanism (1-4).

Table 1 Total statistical data, descriptive statistics

Variable	Descriptive Statistics								
	Mean	Valid N	Median	Mode	Freq	Min	Max	Std.Dev.	Skewness
The use of AI systems	1,80	15,00	2,00	1	7	1	4	0,94	1,04
Component 1	3,07	15,00	3,00	3	8	2	4	0,70	-0,09
Component 2	2,80	15,00	3,00	3	11	1	4	0,68	-1,34
Component 3	3,33	15,00	3,00	4	7	2	4	0,72	-0,63
Component 4	3,00	15,00	3,00	3	7	1	5	1,00	0,00

Based on the sample of companies studied, the results of descriptive statistics show a mean value of 1,80 (median of 2,00) in relation to the use of AI systems on a scale of 1,00 to 5,00, which is below average. Looking at the four components of the technological humanism model, the highest mean value of 3,33 (median 3,00) is recorded by component 3, which refers to the use of procedures and processes to achieve employee satisfaction in changing working conditions, and the lowest mean value of 2,88 (median 3,00) is recorded by component 2, which refers to the organization of workplace and ergonomics in accordance with the implementation of new technologies. The results from the sample of companies studied indicate a greater tendency to ensure employee satisfaction as a psychological factor than the organization of workplace and ergonomics as a predominantly physiological factor within the concept of technological humanism.

The presentation of the results of inferential statistics gives an insight into the mutual relations and associations between the variables. Tab. 2 gives an overview of the Spearman's rank correlation results pertaining to the relationship of the use of AI systems in a company, the components of the technological humanism adapted research model (1-4), and the Technological Humanism score. Statistically significant values are marked in bold.

Table 2 Spearman's rank correlation results

Variable	Spearman Rank Order Correlations Marked correlations are significant at p <,05000					
	AI Use	Comp. 1	Comp. 2	Comp. 3	Comp. 4	TH Score
AI Use	1,00	-0,06	-0,27	0,38	**0,71**	0,34
Comp. 1	-0,06	1,00	**0,80**	-0,05	0,06	0,60
Comp. 2	-0,27	**0,80**	1,00	-0,04	-0,01	0,55
Comp. 3	0,38	-0,05	-0,04	1,00	**0,79**	0,70
Comp. 4	**0,71**	0,06	-0,01	**0,79**	1,00	0,74
TH Score	0,34	0,60	0,55	0,70	0,74	1,00

It can be seen that the use of AI systems in a company has no statistically significant association with the Technological Humanism Score. This could be a problem for the surveyed companies if they would like to make the transition towards Industry 5.0, because the use of AI systems and components of technological humanism are an integral part of it [15]. Considering that the respondents were members of top management responsible for decision-making and defining policies and processes within the digital transformation of the company, and that the implementation and use of AI solutions is a very sensitive area that includes a wide range of possible organizational impacts [36], the lack of establishing an organization that supports the human factor, for which they are responsible, is concerning.

It is observed that the use of AI systems has a statistically significant association with only one component of technological humanism, namely Component 4, which represents the existence of an implemented system for long-term management of the quality of work of employed human resources. Component 4 is important and demanding within the organization because it includes continuous improvement, professional development and investment in people, and on the other hand, managing the replacement of human resources that do not meet the required conditions [24]. Further analysis of the interrelationship of variables shows that Component 4 records a statistically significant association with Component 3, which represents the degree of use of procedures and processes to achieve employee satisfaction in changing working conditions. This statistically confirmed association indicates that the companies surveyed associate the psychological characteristic in the form of employee satisfaction with having and acquiring a quality workforce in the long term.

Component 1, which represents the training and education of human resources in the application of new technologies, is very important in the implementation of AI solutions because it enables the acquisition of skills related to AI technology, which results in its competent use, reduced misunderstandings and minimization of risks [37]. The absence of its statistically significant association with the use of AI systems in the surveyed companies represents a potential problem when implementing these digital solutions.

Observing the mutual relationship between the components of technological humanism, Component 1 records a statistically significant association with Component 2, which represents the degree of the organization of workplace and ergonomics in accordance with the implementation of new technologies. This enables an effective transition with training and education aimed at adapting employees to different workplace conditions in the company brought about by the introduction of new technologies.

4 CONCLUSION

Artificial Intelligence (AI) is a technology that has already been implemented in various spheres of life and business, so that it can be called just relatively new. As it enables actions and functions that no technological solution from the past could perform independently, it represents a tool that requires understanding, clear interpretation, tractability and reliability trustworthiness. In order to achieve long-term benefits from AI use for people and organizations that include that this technology is at the service of people, it is necessary to include technological humanism, which is dedicated to ensuring the protection of human dignity in the technological developments accompanying the digital age [8] and which represents an important part of Industry 5.0. Published research in the field of AI, Industry 5.0 and technological humanism has shown possible differences of viewpoints from the top management in relation to other employees. This could result in an organizational structure set up by top management that does not correspond to the needs or expectations of other employees regarding the humanistic approach to the implementation of new technologies.

A new study conducted on a sample of a larger number of companies from different manufacturing sectors shows the absence of a statistically significant association between the use of AI systems and the implementation of the concept of technological humanism. Since members of the top management are responsible for decision-making and the organization of the company, the results show the extent to which they take into account the humanistic needs of employees. Based on the results of the statistical analysis and statistically significant associations, an association is visible between the use of AI systems in the company in a way that ensures the success of the company's business through the long-term provision of a quality workforce, and the absence of most of the components that denote the sociological values of technological humanism, which includes physiological and psychological factors, important for the well-being of employees. This may be a cause for concern because the implementation of AI technology was not associated to the human aspects of business, which may result in the failure of its effective use [38]. Within the companies studied, the fundamental goal of AI, which should be the preservation of human values and the advancement of social good [39] has not been met, and the possible impact of advanced AI systems, which could result in consequences for human life and society with the potential to lead to practically irreversible changes [36] has not been considered. If the implementation of AI as a new sophisticated technology, which brings numerous benefits but also risks, is not handled correctly from the very beginning, the damage done can be very difficult to repair and could have significant negative consequences on the company and people as a whole.

Since the research was conducted on a small sample of companies, this paper calls for new research in the field of AI implementation in the manufacturing sector. It contributes to the existing knowledge base by identifying areas that need to be focused on, so that the application of AI technology in manufacturing can be of real benefit to the company and people. Attention should also be paid to the specific areas identified in this paper when implementing Industry 5.0, as AI is an integral part of it.

5 REFERENCES

[1] Ryalat, M., El Moaqet, H., & Al Faouri, M. (2023). Design of a smart factory based on cyber-physical systems and Internet of Things towards Industry 4.0. *Applied Sciences, 13*(4), 2156. https://doi.org/10.3390/app13042156

[2] Jeske, T., Würfels, M., & Lennings, F. (2021). Development of digitalization in production industry–Impact on productivity, management and human work. *Procedia Computer Science, 180*, 371-380. https://doi.org/10.1016/j.procs.2021.01.358

[3] Sheikh, H., Prins, C., & Schrijvers, E. (2023). Artificial intelligence: definition and background. In *Mission AI: The new system technology*, Cham: Springer International Publishing, 15-41. https://doi.org/10.1007/978-3-031-21448-6_2

[4] Xu, Y., Liu, X., Cao, X., Huang, C., Liu, E., Qian, S., & Zhang, J. (2021). Artificial intelligence: A powerful paradigm for scientific research. *The Innovation, 2*(4). https://doi.org/10.1016/j.xinn.2021.100179

[5] Passalacqua, M., Cabour, G., Pellerin, R., Léger, P. M., & Doyon-Poulin, P. (2024). Human-centered AI for industry 5.0 (HUMAI5.0): Design framework and case studies. In *Human-centered AI*, Chapman and Hall/CRC, 260-274. https://doi.org/10.1201/9781003320791-27

[6] Plathottam, S. J., Rzonca, A., Lakhnori, R., & Iloeje, C. O. (2023). A review of artificial intelligence applications in manufacturing operations. *Journal of Advanced Manufacturing and Processing, 5*(3), 10159. https://doi.org/10.1002/amp2.10159

[7] ESADE. (2020). *Humanismo Tecnológico o cómo hacer al ser humano el centro de la automatización global*. Madrid.

[8] ESADE. (2020). *Humanismo tecnológico, Conclusiones del Foro de Humanismo Tecnológico*, Madrid, 2020.

[9] Tavares, M. C., Azevedo, G., & Marques, R. P. (2022). The challenges and opportunities of era 5.0 for a more humanistic and sustainable society—a literature review. *Societies, 12*(6), 149. https://doi.org/10.3390/soc12060149

[10] Werthner, H., Ghezzi, C., Kramer, J., Nida-Rümelin, J., Nuseibeh, B., Prem, E., & Stanger, A. (2024). *Introduction to digital humanism: A Textbook*. https://doi.org/10.1007/978-3-031-45304-5

[11] Hernando, A. (2022). *Humanismo digital: la tecnología al servicio de las personas y del propósito de las empresas*. Institute for Social Innovation. Barcelona.

[12] Dmitrieva, E., Balmiki, V., Lakhanpal, S., Lavanya, G., & Bhandari, P. (2024). AI Evolution in Industry 4.0 and Industry 5.0: An experimental comparative assessment. BIO Web of Conferences. *EDP Sciences, 86*, 01069. https://doi.org/10.1051/bioconf/20248601069

[13] Chauhan, C., Singh, A., & Luthra, S. (2021). Barriers to industry 4.0 adoption and its performance implications: An

empirical investigation of emerging economy. *Journal of cleaner production, 285*, 124809. https://doi.org/10.1016/j.jclepro.2020.124809

[14] Rožanec, J. M., Novalija, I., Zajec, P., Kenda, K., Tavakoli Ghinani, H., Suh, S., ..., & Soldatos, J. (2023). Human-centric artificial intelligence architecture for industry 5.0 applications. *International journal of production research, 61*(20), 6847-6872. https://doi.org/10.1080/00207543.2022.2138611

[15] Tóth, A., Nagy, L., Kennedy, R., Bohuš, B., Abonyi, J., & Ruppert, T. (2023). The human-centric Industry 5.0 collaboration architecture. *MethodsX, 11*, 102260. https://doi.org/10.1016/j.mex.2023.102260

[16] Chamola, V., Hassija, V., Sulthana, A. R., Ghosh, D., Dhingra, D., & Sikdar, B. (2023). A review of trustworthy and explainable artificial intelligence (xai), *IEEe Access*. https://doi.org/10.1109/ACCESS.2023.3294569

[17] Zhu, J., Liapis, A., Risi, S., Bidarra, R., & Youngblood, G. M. (2018). Explainable AI for designers: A human-centered perspective on mixed-initiative co-creation. *The IEEE Conference on Computational Intelligence and Games (CIG2018)*, 1-8. https://doi.org/10.1109/CIG.2018.8490433

[18] Peter, M. K., Kraft, C., & Lindeque, J. (2020). Strategic action fields of digital transformation: An exploration of the strategic action fields of Swiss SMEs and large enterprises. *Journal of Strategy and Management, 13*(1), 160-180. https://doi.org/10.1108/JSMA-05-2019-0070

[19] Ciccarelli, M., Papetti, A., & Germani, M. (2023). Exploring how new industrial paradigms affect the workforce: A literature review of Operator 4.0. *Journal of Manufacturing Systems, 70*, 464-483. https://doi.org/10.1016/j.jmsy.2023.08.016

[20] Koldewey C., Hobscheidt D., Pierenkemper C., Kühn A. & Dumitrescu R. (2022). Increasing firm performance through industry 4.0 - A method to define and reach meaningful goals. *Sci., 4*(4), 39. https://doi.org/10.3390/sci4040039

[21] Salvatore M., & Stefano R. (2021). Smart operators: How Industry 4.0 is affecting the worker's performance in manufacturing contexts. *Procedia Computer Science, 1*(180), 958. https://doi.org/10.1016/j.procs.2021.01.347

[22] Alves, J., Lima, T. M., & Gaspar, P. D. (2023). Is industry 5.0 a human-centred approach? A systematic review. *Processes, 11*(1), 193. https://doi.org/10.3390/pr11010193

[23] Hofkirchner, W. (2021). The Future of anthroposociogenesis: panhumanism, anthroporelational humanism and digital humanism. *The 2021 Summit of the International Society for the Study of Information Proceedings, 81*(1), 114. https://doi.org/10.3390/proceedings2022081114

[24] Vukelić, Ž., Cajner, H., & Barić, G. (2024). Research model of the degree of technological humanism in manufacturing companies in the transformation towards Industry 5.0. *Tehnički glasnik, 18*(3), 410-417. https://doi.org/10.31803/tg-20240502091110

[25] Vukelić, Ž., Cajner, H., & Trstenjak, M. (2024). The aspect of technological humanism in the implementation of robotic systems (RS) and artificial intelligence (AI) in Industry 5.0. In *Proceedings of the 15th International Scientific Conference MMA-Flexible Technologies* (pp. 143-146). Novi Sad: Faculty of technical sciences, Department of production engineering. https://doi.org/10.24867/MMA-2024-04-004

[26] Pech, M., & Vaněček, D. (2022). Barriers of new technology introduction and disadvantages of industry 4.0 for industrial enterprises. *Serbian journal of management, 17*(1), 197-206. https://doi.org/10.5937/sjm17-30453

[27] Schermerhorn, J. R. (2013). *Management*. Hoboken: John Wiley & Sons.

[28] Olsson, A. K., Eriksson, K. M., & Carlsson, L. (2025). Management toward Industry 5.0: A co-workership approach on digital transformation for future innovative manufacturing. *European Journal of Innovation Management, 28*(1), 65-84. https://doi.org/10.1108/EJIM-09-2023-0833

[29] Adel, A. (2022). Future of industry 5.0 in society: Human-centric solutions, challenges and prospective research areas. *Journal of Cloud Computing, 11*(1), 1-15. https://doi.org/10.1186/s13677-022-00314-5

[30] Pouyakian, M. (2022). Cybergonomics: Proposing and justification of a new name for the ergonomics of Industry 4.0 technologies. *Frontiers in Public Health, 10*, 1012985. https://doi.org/10.3389/fpubh.2022.1012985

[31] Adisa T. A. (2024). *HRM 5.0: Unpacking the digitalisation of human resource management*. Springer. https://doi.org/10.1007/978-3-031-58912-6

[32] Tomašević, A. N. (2023). Reshaping the future of work: Navigating the impacts of lifelong learning and digital competences in the era of 5.0 industry. *Social informatics journal, 2*(1), 1-6. https://doi.org/10.58898/sij.v2i1.01-06

[33] Sony, M., & Naik, S. (2020). Critical factors for the successful implementation of Industry 4.0: A review and future research direction. *Production Planning & Control, 31*(10), 799-815. https://doi.org/10.1080/09537287.2019.1691278

[34] Leon, R. D. (2023). Employees' reskilling and upskilling for industry 5.0: Selecting the best professional development programmes. *Technology in Society, 75*, 102393. https://doi.org/10.1016/j.techsoc.2023.102393

[35] Li, L. (2022). Reskilling and upskilling the future-ready workforce for industry 4.0 and beyond. *Information Systems Frontiers*, 1-16. https://doi.org/10.1007/s10796-022-10308-y

[36] Gruetzemacher, R., & Whittlestone, J. (2022). The transformative potential of artificial intelligence. *Futures, 135*, 102884. https://doi.org/10.1016/j.futures.2021.102884

[37] Markus, A., Pfister, J., Carolus, A., Hotho, A., & Wienrich, C. (2024). Effects of AI understanding-training on AI literacy, usage, self-determined interactions, and anthropomorphization with voice assistants. *Computers and Education Open, 6*, 100176. https://doi.org/10.1016/j.caeo.2024.100176

[38] Ejsmont, K. (2021). The Impact of Industry 4.0 on Employees—Insights from Australia. *Sustainability, 13*(6), 3095. https://doi.org/10.3390/su13063095

[39] Tsanov, I. (2024). The role of social psychology in the creation of ethical AI systems. In *IEEE International Conference Automatics and Informatics (ICAI2024)*, 142-147. https://doi.org/10.1109/ICAI63388.2024.10851581

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Bicycle Transport – An Original Solution for Building Cycle Paths on Unused Railway Tracks

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Abstract: The issue of functional cycle paths is a long-term pressing problem in Slovakia. Cycling combines many benefits that are related to a healthy lifestyle, an environmental approach to transport and, last but not least, the development of the given region. Construction of modular cycle paths on unused railway tracks is one of the possible and modern approaches. The total length of long-term unused railway tracks in Slovakia is approximately 180-220 kilometers. This approach offers several benefits, such as the meaningful use of unused tracks, addressing legal aspects of land use, recycling of unusable waste, or the possibility of quick restoration of the original railroad track. The aim of this article is to present an innovative project for building cycle paths on unused railway lines with the meaningful use of plastic and rubber waste.

Keywords: bicycle transport; modular; original patent solution; prefabricated panels; railway tracks; removable system

1 INTRODUCTION

Current statistical data of the Ministry of Transport and Construction of the Slovak Republic for the year 2020 indicate that the total length of railway tracks in Slovakia is approximately 3,650 km, of which more than 180 kilometers have not been used for a long time [1]. The main reasons are the long-term lack of interest in the use of rail transport by shippers, no declaration of a possible interest in the resumption of rail transport in the future, a decrease in passenger numbers due to the loss of job opportunities in the region of interest, unsatisfactory technical condition of the track or the lack of strategic development near the tracks. The solution proposed by the presented project is to enable the temporary or long-term use of non-operational railway tracks as routes for alternative modes of transport, such as cycle paths or pedestrian paths. Under Act no. 513/2009, [2] as amended, on railways the owner may lease or sell the unused railway tracks to a municipality, an association of municipalities or to a self-governing region to be used for transport purposes [3]. The use of the railway for operating bicycle/ transport, for temporary construction of local traffic paths – including a bicycle route or a footpath – is possible with the approval of the Ministry of Transport and Construction for the period of 3 years minimum, a maximum of 10 years with the possibility of another 10 - year maximum extension [2].

In addition, as early as 2013, the Slovak government approved the draft of the National strategy for the development of bicycle transport and bicycle tourism in the Slovak Republic [3]. One of its basic goals was to make bicycle transport equal to other types of transport, to improve the visibility of cyclists in the transport space, to facilitate cycling tourism, to support tourism and improve mobility, and to improve the population's awareness of economic, ecological and health benefits of bicycle transport.

2 A PROGRESSIVE SOLUTION

The number of abandoned, non-functional and unprofitable railway tracks in Slovakia presents a problem that may be addressed in a meaningful way.

There are a number of original solutions for overlapping rails, [6-10]. The advantage of the solution we propose is based on a simple principle (only two components), easy assembly (without screw connections), and the possibility of creating customizable surface and 3D solutions. The goal of the proposed solution is to cover such tracks with a modular prefabricated panel system [4]. The proposed modular system is based on two assembly elements – a prefabricated panel and a connector as illustrated in Fig. 1.

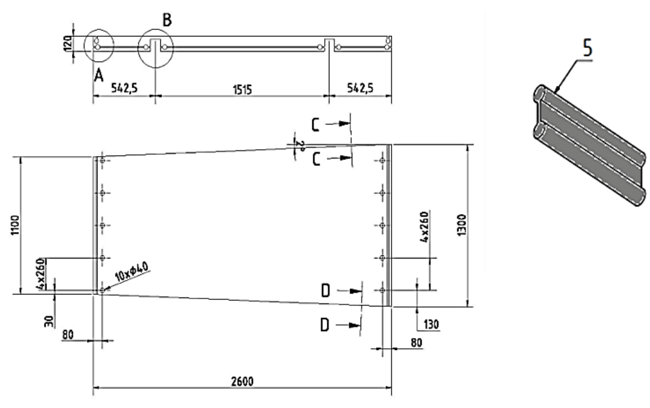

Figure 1 Prefabricated panel system, a) prefabricated panel; b) connector

The prefabricated panel is made up of a flat body with a square geometric shape made of composite concrete containing secondary raw materials of plastic or rubber. The body of the panel has a continuous groove (3) on the sides around the perimeter, Fig. 2. Each corner of the body has two mutually perpendicular holes (4) in the grooves (3) set off from the corner edge on the lateral sides to enable overlapping joints; the diameters of the holes (4) are larger than the width of the groove (3). The body has two continuous anchoring profile grooves (6) spaced from each other on the bottom side between the opposite sides of the body and two holes (4) in the groove (3) spaced on the sides of the profile groove (6) for creating a clamping connection between the body and external carrier, whilst the diameters of the holes (4) are larger than the width of the groove (3).

The prefabricated panel system consists of a set of prefabricated panels (1) in at least a 2D arrangement, which are connected to each other by overlapping joints (2) between adjacent corners of the overlapped panels (1). The overlapping joint (2) fits into the hole (4) of one adjacent panel (1) and a complementary connecting member (5) fits into the hole (4) of the second adjacent panel (1), and into the adjacent grooves (3) of both adjacent panels (1). The prefabricated panels (1) have clamping joints (8) between the external carriers, where the external carriers fit into continuous anchoring profile grooves (6), whilst complementary connectors (5), whose free ends are in clamping contact with external carriers, are inserted into the holes (4) and grooves (3) at the clamping joint (8).

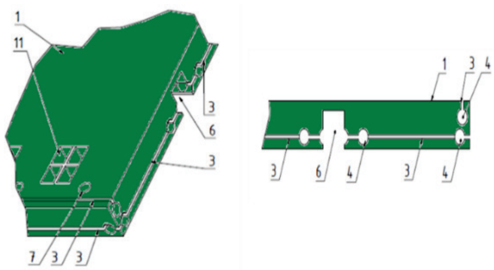

Figure 2 Design of the prefabricated panel

The design of the prefabricated panel system allows the connection of panels in a plane behind each other or next to each other. This makes it possible to cover one track but also, for example, two tracks next to each other or even to cover entire platforms with several tracks. However, the design also enables the creation of a spatial arrangement of panels, Fig. 3.

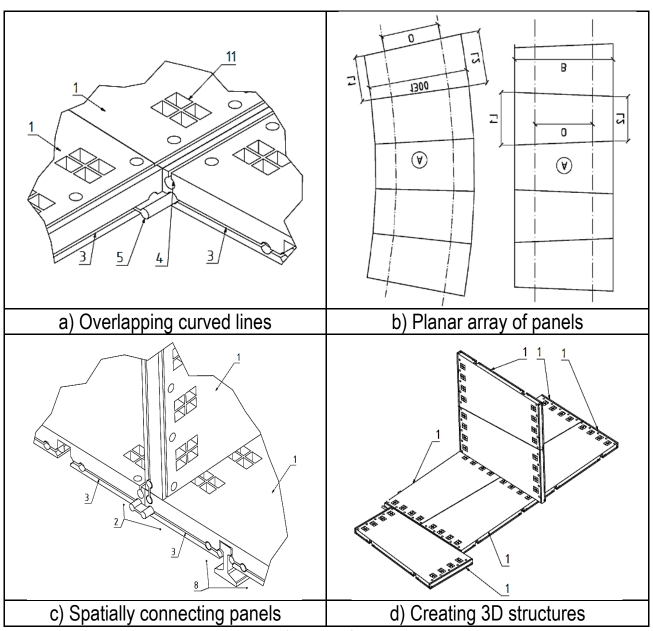

Figure 3 Variability of the prefabricated panel system

The benefits of the prefabricated panel and the prefabricated panel system are the universality, the use of only two mounting elements, and a simple and clean design solution. The assembly is very simple and consists only of inserting the connectors into the appropriate openings of the panels depending on the required joint. These connectors are not accessible from the outside. As a result, it is not possible to disassemble the panel system at any place without mechanical damage. The real possibilities of the prefabricated variable panel system are apparent from Fig. 4. The spatial arrangement of the panels also allows for the construction of small structures, such as shelters for cyclists, tunnels, or barriers against landslides on a slope. However, the panels do not have to be installed on railway tracks but can be used to cover any appropriately prepared surfaces, such as pavements, or various platforms or parking areas.

Figure 4 Mockup of provided options of the variable prefabricated panel system. Legend: 1 - covering of straight tracks, 2 - covering of curved tracks, 3 - covering of platforms, 4 - shelters, 5 - tunnels and underpasses, 6 - protection against landslides, 7 - easy bridging

Figure 5 Robotic panel laying

In the proposed solution for building cycle paths, lighting was also considered. Red lights along the track were connected to photovoltaic cells installed on a black pole. Electronic contacts built into the panels served to check the unbreakability of the track. Holes in the panels were designed for drainage of rainwater and enabled the easy installation of the railing over bridges and other elevated structures. Any utility networks can be installed in the available openings in the panels.

When designing the structure of the panels, efficient and quick assembly or disassembly was considered. The panels were equipped with holes for their attachment during transport and assembly itself. The resulting system thus assumes automated assembly of individual panels, and – in an alternative solution – also the transportation of panels directly by railway and the assembly of panels, e.g., by using a suitable crane system.

Subsequently, the first demonstration models of the panels in real dimensions were produced as illustrated in Fig. 6.

Figure 6 The figure shows the assembly of the demonstration panels

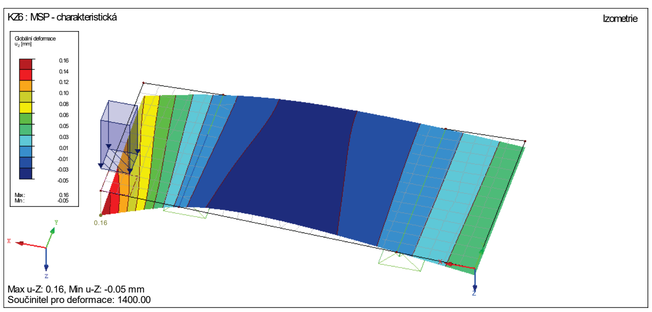

Figure 7 Strength analysis, deflection of the panel - load on the cantilever

An example of the strength analysis of a prefabricated panel is shown in Fig. 7 and Fig. 8. The slab calculation model was created in the Dlubal RFEM program, [5]. The model was linearly supported at the location of the rails. The load was considered in the form of self-weight and a point load of 10 kN from one wheel on the console (Fig. 7) and in the mid- span (Fig. 8). The dimensioning was carried out according to the European standards EN1992-1-1 for the effects of bending moments and shear forces. It is clear that the extreme stress is achieved in the cross section above the rail. To transfer these moments, concrete reinforcement was subsequently designed on the upper and lower surfaces of the panel. The production of our own panels took place in a prefab factory in a standard form, into which reinforcement was inserted and concreting was carried out, as shown in Fig. 9 and 10. Four transport anchors, located on the shorter sides, were intended for lifting the panel.

As a result of the analysis, a proposal was made for the required strength of the panel and its minimum thickness directly above the rails. Subsequently, the final construction of the panel with the required reinforcement was determined. To verify the load-bearing capacity of a typical prefabricated panel, load tests with two load sets were performed – ZS1 – load of the exposed end of the panel and ZS2 – load of the middle of the panel. The designed concrete class was C30/37. A demonstration of the load placed on the edge of the panel is presented below. The loading was performed through distribution plates with dimensions of 0.1 × 0.1 m. The detailed loading scheme is shown in Fig. 11. During the test, the force – FV4 and FV6 (FV5) and the deflections V1 – V6 were monitored.

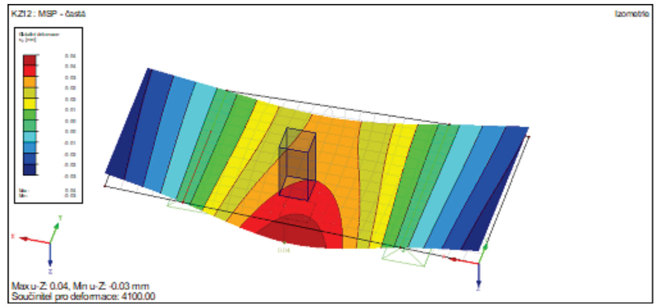

Figure 8 Strength analysis, panel deflection - mid-span load

Figure 9 Form of prefabricated panel with reinforcement

Figure 10 Manufactured prefabricated panel

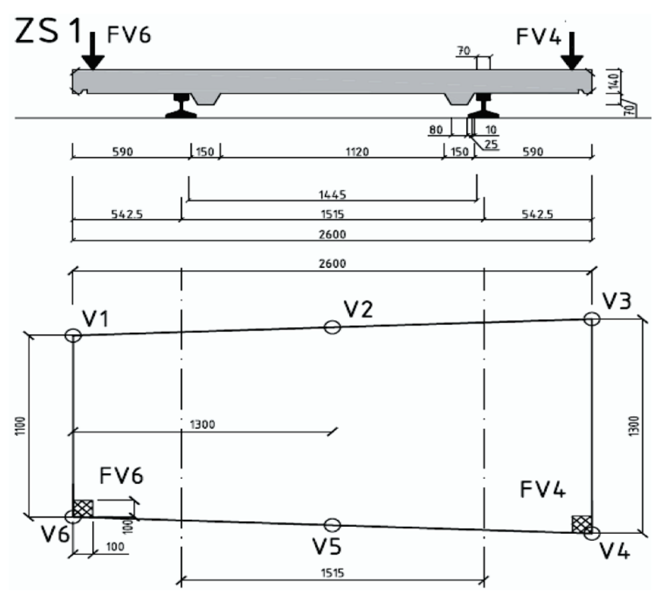

Figure 11 Load scheme

Both ends of the panel were simultaneously loaded with the same static force, Fig. 12.

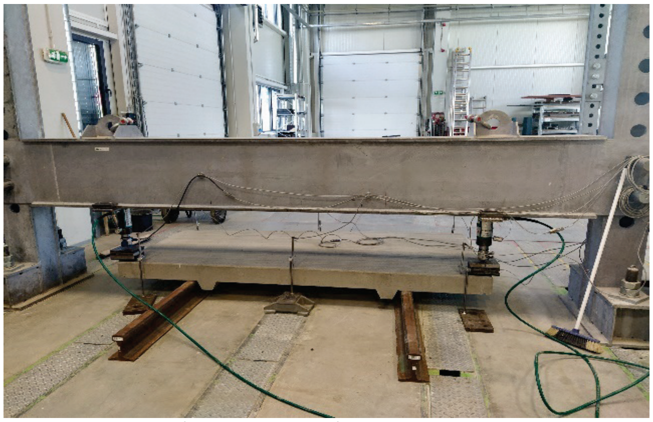

Figure 12 View of the arrangement of the load pins during measurement

The first hairline cracks appeared at approximately 15 kN above the rail. With increasing force, bending cracks gradually began to form in the panel at the upper surface and shear cracks started to form at the console. At a load of approximately 40 kN, more significant cracks with a width of 0.2 mm were formed (at a deformation of the console v6 approximately 5 mm).

From this load level, the panel behaved significantly nonlinearly, deformations increased and cracks developed, the force increased less as shown in Fig. 13. The maximum limit value of the load FV4 was equal to 65 kN and deflection was reached.

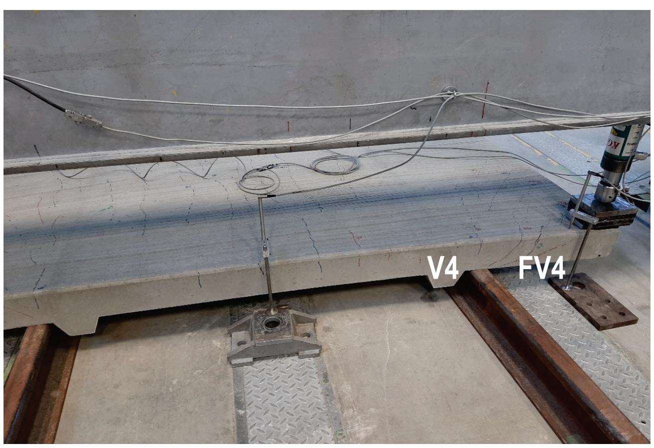

Figure 13 Overall failure of the panel by flexural cracks at the upper surface and shear cracks at the point of solitary force (right)

At the given minimum thickness, it can be subsequently defined how much secondary raw materials can be added to pure concrete, so that the required strength of the concrete composite is maintained.

The calculated weight loss with different composition of the composite is evident from Fig. 14.

When manufacturing the panels, the assumption is that up to 30% of the concrete filler would be made from rubber or plastic waste. The diagram below show the total weight of one panel with the different ratios of the materials used.

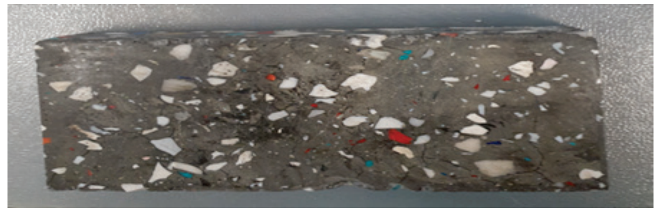

Figure 14 Test sample created in the composition 85 concrete/15 plastic

The final proportions of added waste will depend on the continuous supply of a sufficient amount of waste, as well as on the results of strength analysis and experiments with real panels. The change in panel weight by adding plastic waste can be seen from Fig. 15.

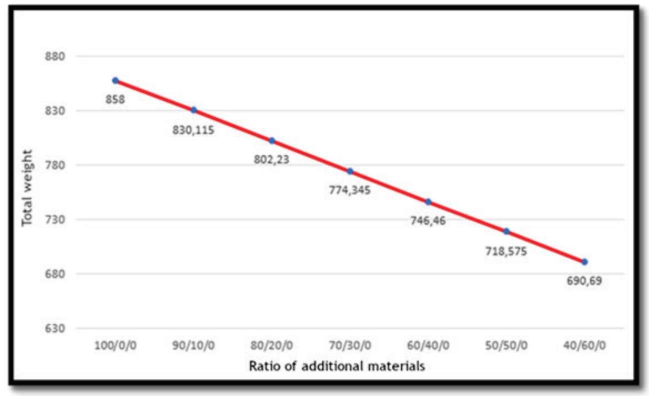

Figure 15 Changing the weight of the panel by adding plastic waste

Based on the results of calculations, experimental tests and the design of the technological production process, the first test section was implemented with real panels, Fig. 16. The objective of this test section was to verify the technological method of production, transport, handling of the manufactured panels and possible problems during laying. All test results were plausible. This created all conditions for the implementation of a pilot project for creating cycle paths on unused railway lines.

Figure 16 The first test section created from real panels

3 CONCLUSION

Slovakia has a total of more than 300 km of minimally used railway tracks. Of these, more than 100 kilometers have not been used for a long time. In general, it can be concluded that Slovak Railways has a problem of maintaining the currently operable tracks. Many foreign countries have turned abandoned railway tracks into Greenways – multifunctional paths- or for other tourist and commercial purposes. Usually, such repurposing was done by dismantling the tracks and then pouring a concrete-asphalt mixture, often also directly in nature.

The aim of this article is to present a new and innovative technology for the use of abandoned railway tracks as a basis for building new cycle paths. The Trailpanel project proposes to transform unused railway tracks into cycle paths without removing the existing rails, just by simply changing their purpose. The idea is based on the installation of prefabricated panels on existing tracks. The present innovative project offers a comprehensive analysis of the possibility of transforming unused railway tracks into functional, modern cycle paths.

The aim of further research of the presented project is to design a suitable optimal composition of the composite material for the production of panels, design a large-volume mold, the final technological process for the production of panels and design a technological line for the serial production of panels. In the production of composite concrete, it is planned to use otherwise unusable waste, mainly from plastics and rubber. During 2025, we plan to implement the first pilot project of a cycle track with a length of approximately 10 kilometers.

The load tests were successfully completed. This is also a prerequisite for the successful use of panels in-situ.

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4 REFERENCES

[1] Regulation no. 513/2009 Coll. 'Act on Railways and Amendments to Certain Acts' electronic resource. Available at: https://www.zakonypreludi.sk/zz/2009-513 (accessed 25.8.2022)

[2] Unified vision of the railway sector in the Slovak Republic – evaluation of the current progress of the revitalisation of railway companies and the determination of their mutual coordination by the Ministry of Transport and Construction of the Slovak Republic, Jednotna_vizia_ZS_SR_pripom.pdf, electronic source. Available at: https://www.mindop.sk/ministerstvo-1/doprava-3/zeleznicna-doprava/jednotna-vizia-zeleznicneho-sektora-v-sr/jednotna-vizia-zeleznicneho-sektora-v-sr-pdf (accessed 25.8.2022)

[3] National strategy for the development of bicycle transport and cycling tourism in the Slovak Republic, electronic resource. Available at: https://www.mindop.sk/ministerstvo-1/doprava-3/cyklisticka-doprava-a-cykloturistika/narodna-strategia-rozvoja-cyklistickej-dopravy-a-cykloturistiky-v-slovenskej-republike-7-8-mb-pdf (accessed 25.08.2022)

[4] Šooš, Ľ., Čačko, V., Chlebo, O., Marek, J., & Šooš, M. (2021). Prefabricated panel and prefabricated panel system: utility model no. 9496, application number 98-2021, date of application 30.6.2021, availability of the utility model 11.5.2022 Banská Bystrica Industrial Property Office of the Slovak Republic 2022, p.12.

[5] Zich, M., & Švaříčková, I. (2022). *Panely cyklostezka*. Brno, Czech Republic, p23. (in Czech)

[6] https://patents.google.com/patent/DE20020443U1/en

[7] https://worldwide.espacenet.com/patent/search/family/007832263/publication/DE19724833A1?q=DE19724833

[8] https://worldwide.espacenet.com/patent/search/family/006519679/publication/DE4419382A1?q=DE4419382%20A1

[9] https://worldwide.espacenet.com/patent/search/family/069630346/publication/FR3099936A1?q=FR3099936%20A1

[10] https://worldwide.espacenet.com/patent/search/family/040289688/publication/GB2466186A?q=GB2466186%20A

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