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INCREASING PRODUCTION EFFICIENCY ON THE EXAMPLE OF THE WINKELMANN SP. Z O.O. PLANT NO. 1 IN LEGNICA

Daniel DĘBOWSKI – Michał BOBIŃSKI – Marek KLIMENT – Paweł JURCZAK

Abstract: The article presents a case study of Winkelmann, a company with a plant located in Legnica that specializes in the production of capacitive water heaters. The analysis concerns activities aimed at increasing production efficiency through infrastructure modernization, plant layout reorganization, and the implementation of new technologies. The considerations combine theoretical and practical perspectives, showing how production management concepts translate into concrete actions.
Keywords: efficiency, optimization, production processes.

Introduction

Production efficiency is one of the fundamental factors determining the competitiveness of modern industrial enterprises. In the era of globalization, increasing customer demands, and cost pressure, organizations face the necessity not only of maintaining high quality but also of continuously increasing the effectiveness and flexibility of manufacturing processes. The ability to optimally utilize resources – both material and human – becomes the basis for building a market advantage. The literature emphasizes that companies that effectively implement process improvement tools can respond faster to environmental changes, minimize costs, and develop innovations [1].

Methods and methodology.

Production efficiency can be defined as the ratio of effects obtained in the production process to the incurred costs. A set of technical and organizational indicators is used to measure this category. The most commonly used is OEE (Overall Equipment Effectiveness), which provides a comprehensive view of the utilization rate of machines and equipment [2] [3]. Other indicators include MTBF (mean time between failures), MTTR (mean time to repair), and MTTF (mean time to first failure), which relate to reliability and maintenance [4]. High values of these indicators indicate the technical efficiency of the machine park and process stability. Literature on production management often emphasizes the importance of Lean Manufacturing, which focuses on eliminating waste (Japanese: muda), and Kaizen, which assumes continuous improvement with the participation of all employees. In turn, TQM (Total Quality Management) and Six Sigma indicate the need for systematic quality monitoring and reduction of process variability. All these approaches find practical application in industrial enterprises that strive to increase efficiency [5] [6].

Company characteristics

Winkelmann is a family-owned company with over a century of tradition, dating back to 1898 in Ahlen (Germany). It has been operating in Poland since 1994, and plant No. 1 in Legnica was established in 1998. It produces buffer tanks and water heaters, and other group plants specialize in the automotive industry and the production of expansion tanks.
The company's strengths include high profitability, access to capital, a favorable location in the Legnica Special Economic Zone (LSSE), long-term experience, and a well-established market

position. Weaknesses include employee turnover and the risk of raw material price fluctuations. SWOT analysis showed the rationale for investing in the development of plant No. 1 and the necessity to increase production capacity in the face of constantly growing demand.
Production at plant No. 1 covers the full manufacturing cycle – from raw steel to finished water heater. The process consists of the following stages: production preparation, welding shop, enameling shop, sewing shop, and final assembly. Each department is responsible for highly specialized operations, and the finished product goes to the finished goods warehouse (Fig. 1).

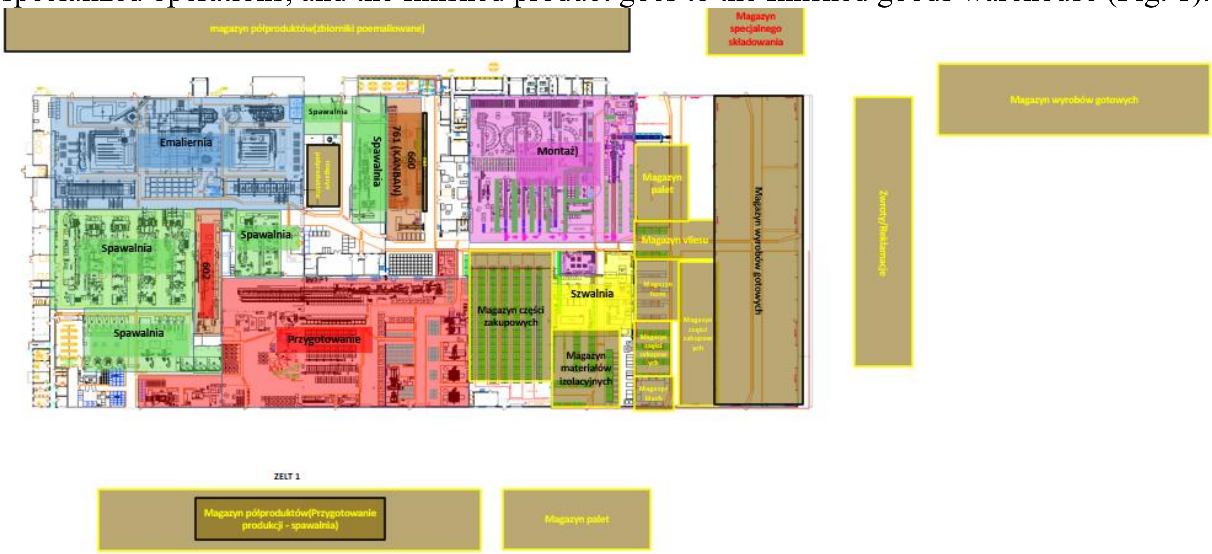


Figure 1: Organizational structure of Winkelmann - Plant No. 1 in Legnica.

The management of Winkelmann, recognizing the growing demand for its products, decided to increase annual production capacity from the current level of 271,000 to 324,000 tanks by 2026. This goal required the implementation of both organizational measures and investments in infrastructure and the machine park. Projects implemented so far include the modernization of the high-bay warehouse, which increased logistical capacity, and the installation of an automatic foil wrapping line, streamlining the packaging of finished products. Both ventures have contributed to an increase in assembly efficiency of approximately 12,000 tanks per year. Development plans include transferring part of the processes to the Reflex plant in Wąbrzeźno, which will relieve the Legnica plant. The reconstruction concept also includes the construction of a new finished goods warehouse and the reorganization of the layout of production halls. The work schedule is divided into stages to minimize the risk of downtime.

Reconstruction stage schedule

The reconstruction plan is divided into nine main stages (Figs. 2-10), starting in the fourth quarter of 2024 and assuming completion of all work by the end of 2026. The main tasks of the first stages include adding a new enamel mixer, starting the reconstruction of the semi-finished product warehouse tent, building temporary tents, and moving the paint shop.
In stage II, it is planned to move the sewing room and the tool shop, and in subsequent stages, the high-bay warehouse, assembly lines, presses, and other key machines. Consistent staging aims to minimize the risk of disruptions and spread construction and assembly work over time – especially during periods of floor curing (approx. 100 days) and the installation of ventilation and exhaust systems. The strategy of breaking it down into stages also allows for flexible adaptation of the schedule depending on the availability of components and production seasonality.

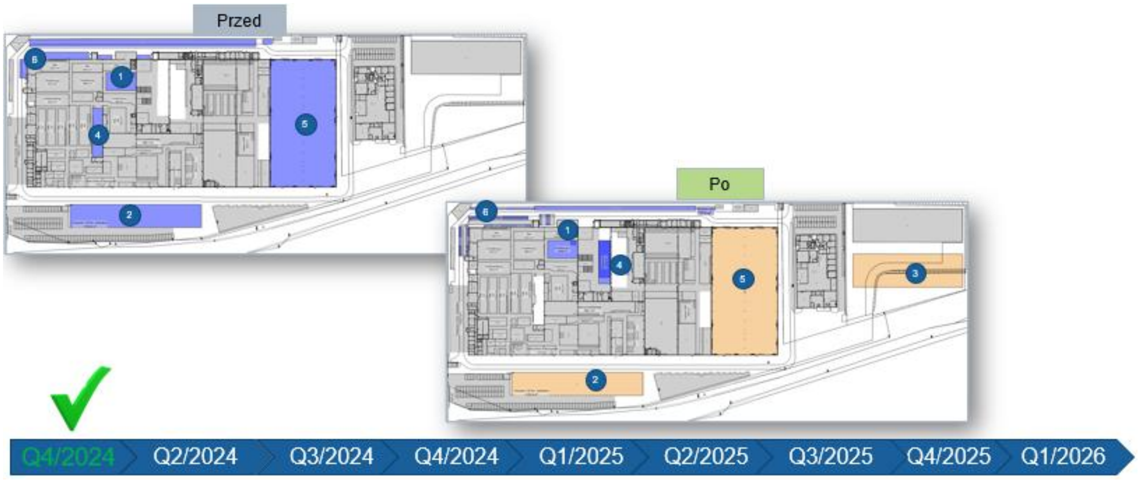


Figure 2: Reconstruction Plan - Stage I: 1-Addition of a new enamel mixer; 2-Start of reconstruction of the semi-finished product warehouse tent; 3-Start of construction of a temporary storage tent; 4 - Transfer of paint shop; 5 - Pouring the floor in halls 7 and 8 (concrete bond approx. 100 days); 6 - Construction of a rack warehouse for enameled tanks + fire wall.

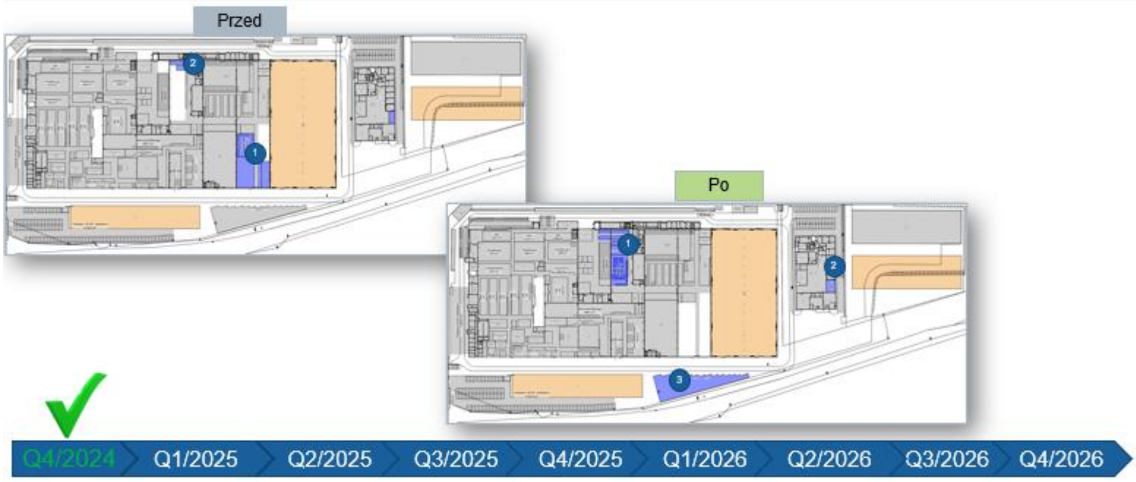
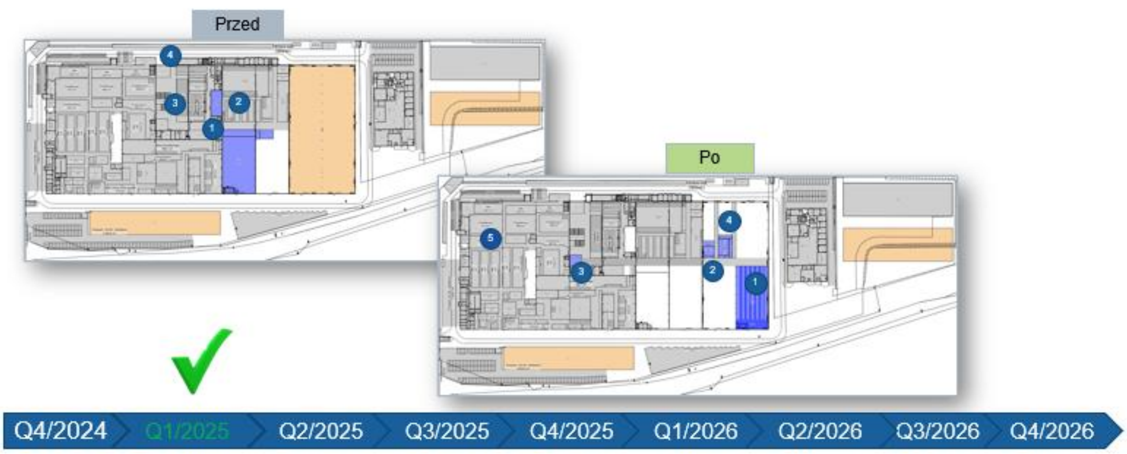


Figure 3: Reconstruction Plan - Stage II: 1 - Transfer of the foil sheathing and foil warehouse; 2 - Relocation of the tool shop; 3 - Roofing of the pallet warehouse.



[Figure 4: Reconstruction Plan - Stage III: 1-Transfer of the high-bay warehouse; 2-Transfer of assembly line No. 7; 3-Transfer of the edge press (SAFAN) to the temporary location; 4-Transfer of the workshop; 5-Replacement of the set of enamel vats (etching).

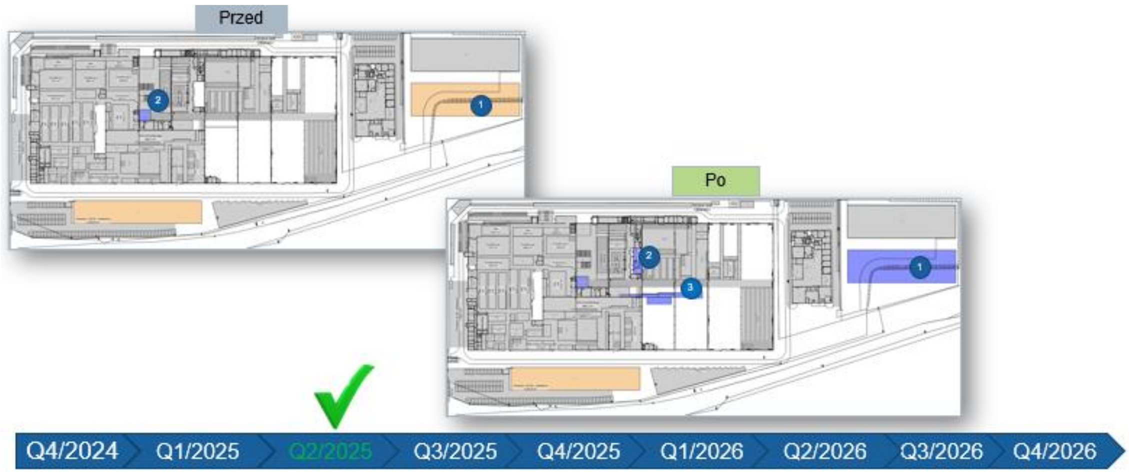


Figure 5: Reconstruction Plan - Stage IV: 1-Completion of the temporary tent construction; 2-Transfer of the edge press (SAFAN) to the target location; 3-Start of construction of machine foundations for pipe production (OTTOMILS).

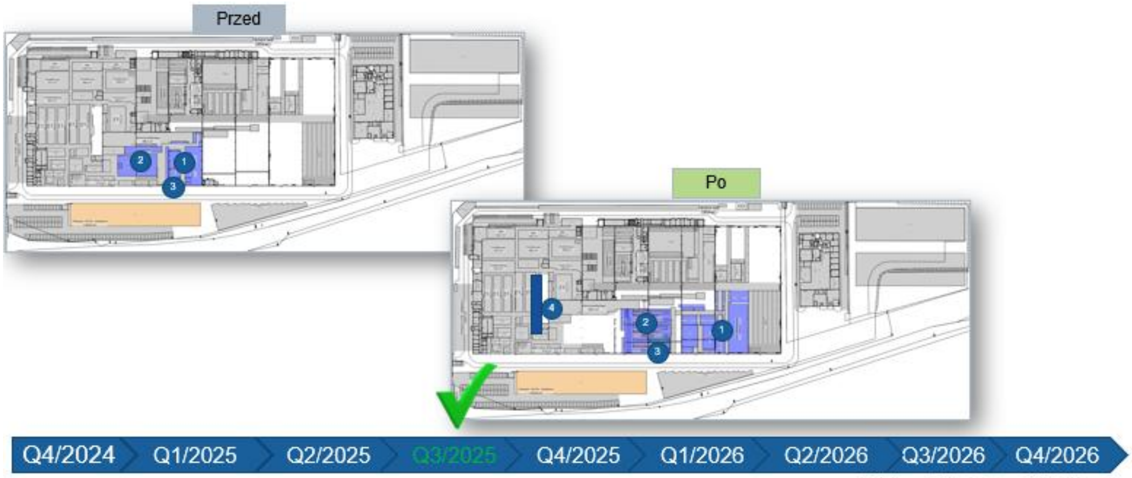


Figure 6: Reconstruction Plan – Stage V: 1-Transfer of the sheet metal processing area and steel warehouse; 2-Transfer of spiral production machines and pipe warehouse; 3-Transfer of the steel disc cutting machine; 4-Construction of a new welding line 4.1 (LS4.1).

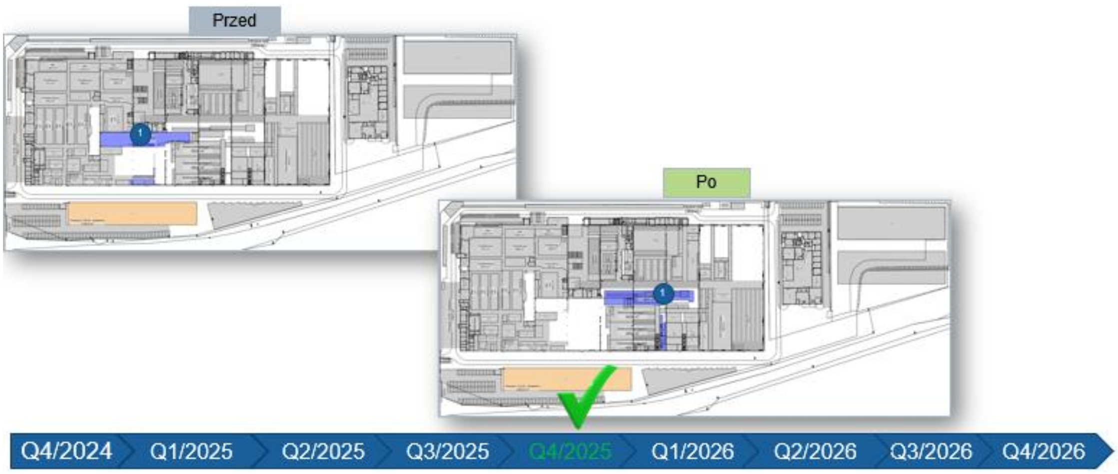


Figure 7: Reconstruction Plan - Stage VI: 1-Transfer of the pipe production machine (OTTOMILS).

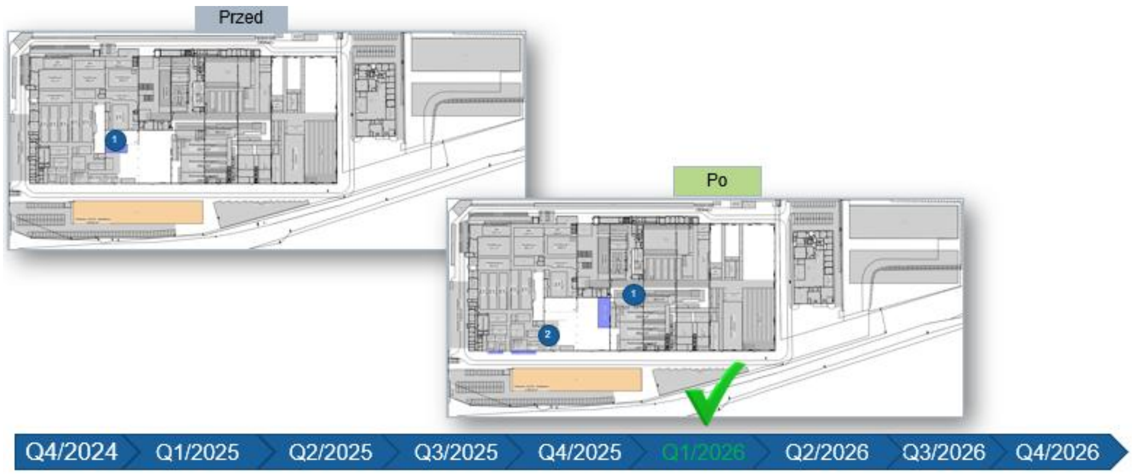


Figure 8: Reconstruction Plan - Stage VII: 1-Transfer of threading machines; 2-Installation of extraction and ventilation in the new area for the welding shop.

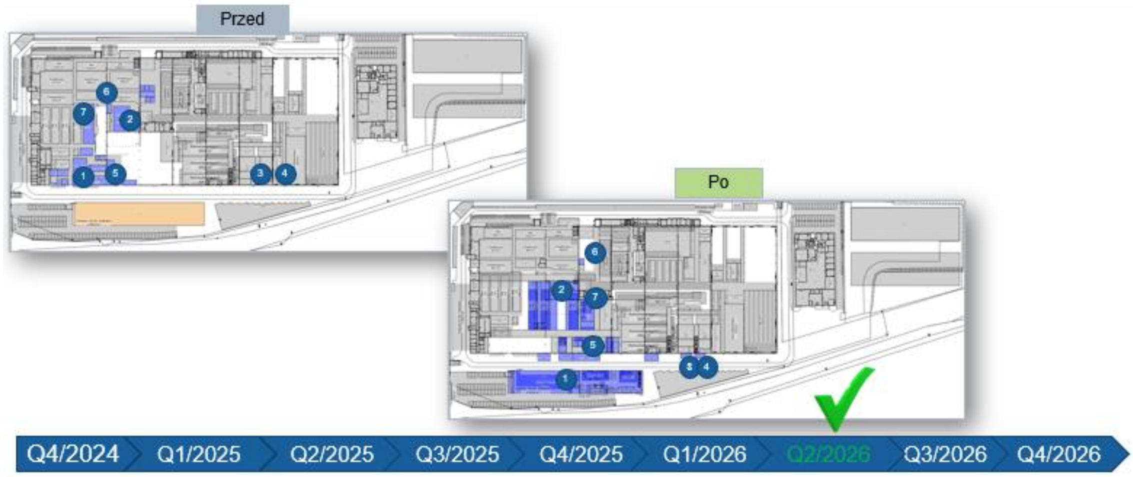


Figure 9: Reconstruction Plan - Stage VIII: 1-Transfer of the stamping plant and semi-finished products warehouse (lids); 2-Transfer of welding line No. 6 (LS6); 3-Transfer of the welding shop offices to temporary containers; 4-Transfer of the enameling shop offices to temporary containers; 5-Transfer of spiral bar stands + new welding robots; 6-Transfer of the special welding station to a temporary location; 7-Transfer of welding line No. 5 (LS5).

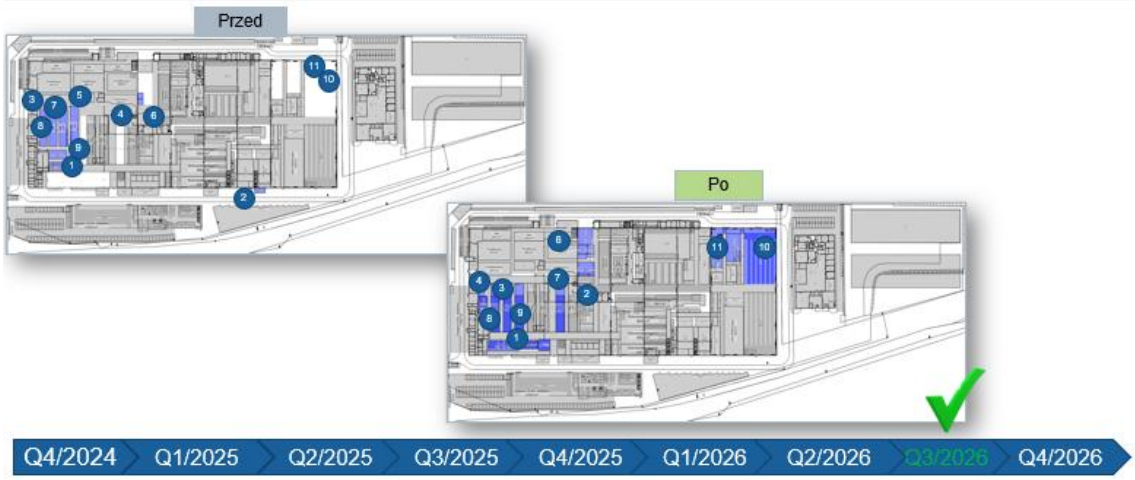


Figure 10: Reconstruction Plan - Stage IX: 1-Transfer of lid and bottom welding stations; 2-Transfer of welding shop offices to the target location; 3-Transfer of welding line No. 1 (LS1); 4-Transfer of water

testing stations; 5-Dismantling of welding line No. 4 (LS4); 6-Construction of the enameling office; 7-Transfer of welding line No. 3 (LS3); 8-Transfer of welding line No. 2 (LS2); 9-Transfer of welding line No. 4 (LS4); 10-Installation of a racking system in the new part of the high-bay warehouse; 11-Construction of a tunnel connecting the assembly with the new finished goods warehouse.

Conclusions

The case study of Winkelmann shows that increasing production efficiency is a multi-stage process, combining elements of operational management and capital investment. Effective actions include both the implementation of modern technologies and automation, as well as the reorganization of the plant layout, the development of employee competencies, and adaptation to changing market conditions. The study confirms that only a comprehensive approach allows meeting the growing demands of customers and maintaining competitiveness in a dynamic market environment.

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HARMONISED APPROACH FOR MEASURING BRAKE PARTICLE EMISSIONS

Miroslav DADO – Janka SZABOVÁ – Jozef SALVA – Marián SCHWARZ

Abstract: Brake wear is a substantial contributor to non-exhaust particulate matter (PM) emissions, particularly in urban environments, where it plays a notable role in air quality degradation. These emissions, characterized by high concentrations of metals and fine particles, are associated with potential adverse health effects. Accurate and reproducible sampling of brake wear aerosols is essential for quantifying their environmental and health impacts and for supporting evidence-based regulatory frameworks. The aim of this paper is to characterize a harmonised methodology for measuring brake wear particulate matter and particle number emissions from brakes used on light-duty vehicles.
Keywords: brake wear particles, emissions test, measuring, harmonized methodology, design requirements

Introduction

Non-exhaust emissions, particularly those originating from brake wear, have become an increasing concern in the context of urban air quality and public health [1]. Brake wear particles, consisting of a complex mix of metals, oxides, and carbonaceous materials, are predominantly emitted in the fine and ultrafine size ranges, posing potential risks to human health and the environment. Unlike tailpipe emissions, brake particle emissions are not mitigated by conventional exhaust after-treatment technologies and can contribute significantly to airborne particulate matter (PM), including ultrafine particles. With the growing prevalence of electric and hybrid vehicles, where regenerative braking reduces but does not eliminate mechanical braking, the relative importance of brake emissions in total vehicular PM emissions is expected to rise [2-4].

Recognizing this issue, the European Commission has incorporated brake particle emissions into the EURO 7 regulation [5], marking the first time that regulatory limits will be applied to non-exhaust particle sources. Under EURO 7, vehicles will be subject to standardized testing procedures and particle number (PN) limits for brake wear emissions, necessitating harmonised and reproducible measurement methods across test facilities. Efforts to quantify brake particle emissions have been challenged by the lack of standardized methodologies, resulting in inconsistent data and limited comparability across studies and regulatory assessments. Variations in test setups, airflow management, sampling locations, and measurement techniques have contributed to significant uncertainties in both PN and particle mass (PM) measurements. However, the accurate and repeatable quantification of brake wear particle emissions remains technically challenging. Existing discrepancies in enclosure design, airflow control, sampling configurations, and instrumentation can lead to significant measurement variability. To support regulatory implementation and ensure data comparability, there is a critical need for a harmonised approach to measuring brake wear emissions.

The aim of this paper is to characterize a harmonised methodology for measuring of brake wear particulate matter and particle number emissions from brakes used on light-duty vehicles.

Overall test system layout

The technical system to perform brake emissions tests requires a robust integration of several subsystems to ensure the drive cycle, cooling air, dynamometer control, brake enclosure, sampling tunnel, aerosol sampling systems, and data collection. Figure 1 provides a layout that includes the minimum required subsystems to carry out a brake emissions test using a brake dynamometer. The illustrated layout features a climatic conditioning unit (1) with variable flow fan(s) that supplies the setup with conditioned air. The conditioned air provides clean and continuous cooling to the brake assembly, and it transports the aerosol from the enclosure into the sampling tunnel and the PM/PN sampling probes. The cooling air entering the test system shall pass through a filter (2) and be monitored by temperature and humidity sensors (3) placed upstream of the brake enclosure. The conditioned air enters a brake enclosure (4) designed to fit the entire assembly of the brake (5) under testing. The brake dynamometer (6) enables and controls the testing of the brake. The enclosure is directly connected to the sampling tunnel (7) near the end of which three (or four) sampling probes (8) are mounted. The sampling probes are used to extract the aerosol from the tunnel towards the PM and PN measurement setup (9). A flow measurement device (10) is installed in the tunnel downstream of the sampling plane.

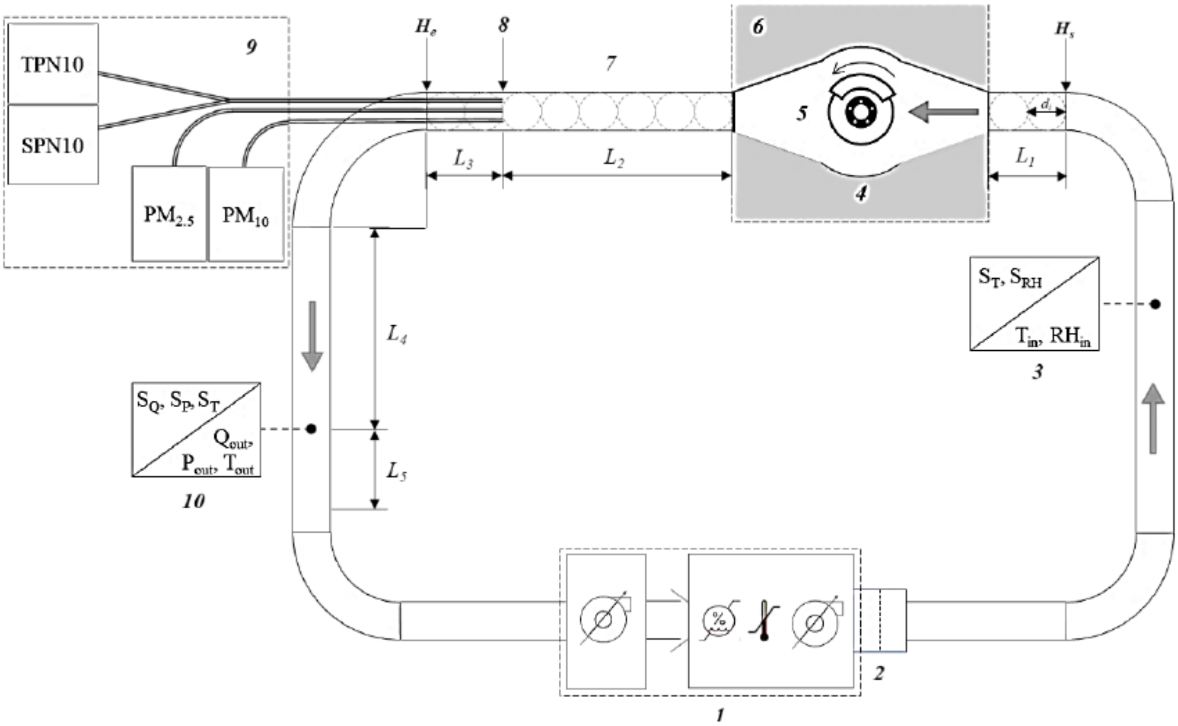

Fig. 1 Indicative layout for performing brake emissions test [6]

A brake emissions test includes three test sections. Each section contains one or more trips with a series of events. The main events which induce brake work and generate brake emissions are the deceleration events. The three sections of the brake emissions test are:

- Brake cooling adjustment,
- Brake bedding,
- Brake emissions measurement [6].

Design requirements for the brake enclosure

The brake enclosure functions as a controlled test chamber in which the brake assembly is installed during brake emissions testing. It is a sealed system designed to prevent the ingress of ambient air, thereby eliminating the risk of contamination in the airflow surrounding the brake assembly. The enclosure facilitates the delivery of uniform, conditioned air to ensure consistent brake cooling and efficient aerosol transport into the sampling tunnel. Design specifications for the enclosure establish standardized criteria to ensure comparability between test systems with respect to cooling performance and particle transport efficiency. An indicative shape of the enclosure with the principal dimensions is illustrated in Figure 2.

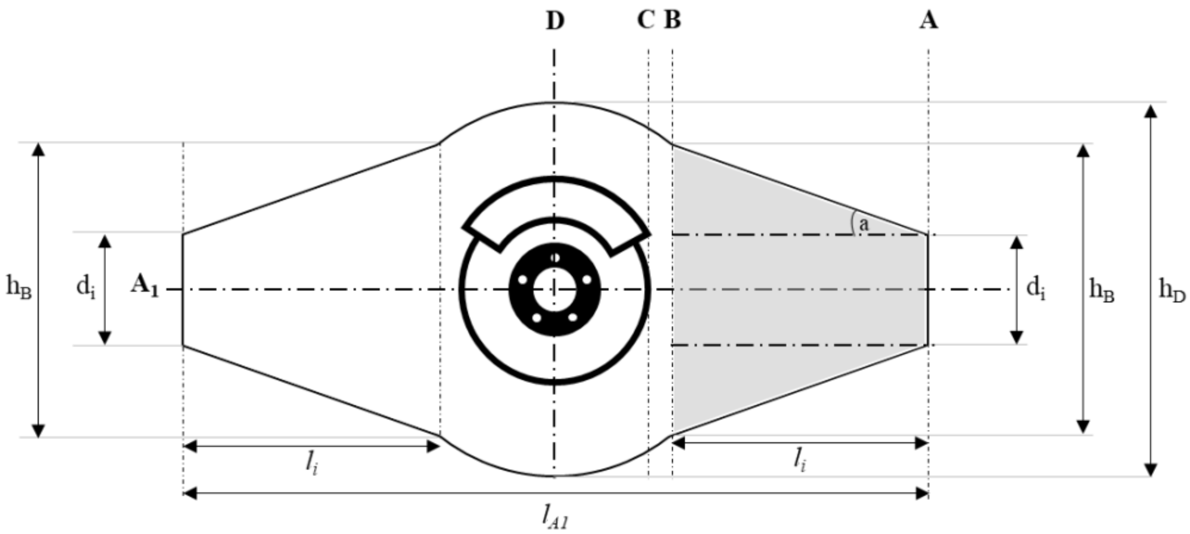

Fig. 2 Shape of the brake enclosure and its main dimensions [6]

The enclosure is defined by one horizontal (A_1) and four vertical planes (A, B, C, D). The brake enclosure shall have two conical or trapezoidal sections intersecting with a cylinder at the centre concentric to the axis of the brake rotation. The inlet and outlet cross-sections shall be designed to ensure smooth transition angles ($15° \leq a \leq 30°$) in order to avoid sudden changes in cross-section shape or size. The airflow at the entrance of the enclosure shall remain turbulent with a Reynolds number of at least 4000 for all airflow testing settings to ensure sufficient mixing. The transition points between the segments shall not have any imperfections or features that may collect brake particles that could become airborne later during the test. The surfaces of the brake enclosure that come into contact with the aerosol shall have a seamless construction. Stainless steel with an electropolished finish (or equivalent) shall be used to attain an ultra-clean and ultra-fine surface and to enhance corrosion resistance. The minimum specifications related to the dimensions of the brake enclosure are described below:

- Plane A_1's length shall be between 1200 mm and 1400 mm (1200 mm $\leq l_{A1} \leq$ 1400 mm),
- Plane D's height shall be between 600 mm and 750 mm (600 mm $\leq h_D \leq$ 750 mm),
- Height at Plane B (h_B) is such that the h_B/h_D ratio is always greater than 60 per cent (h_B/h_D > 60 %),
- The maximum axial depth of the brake enclosure at Plane D (parallel to the brake rotation axis) shall be between 400 mm and 500 mm [6].

Design requirements for the sampling tunnel and sampling plane

The sampling tunnel is defined as the part between the outlet of the brake enclosure and the inlet of the sampling probes. There are two possibilities for the design of the sampling tunnel: a layout without a bend and a layout with one bend. The testing facility shall ensure the design of the sampling tunnel meets the following requirements:

- The cooling air shall flow through round ducts with no variations in the cross-section between the enclosure exit and the sampling plane,
- Stainless steel with an electropolished finish (or equivalent) shall be used for the surfaces of the tunnel that come into contact with the aerosol,
- Ducts shall have a constant inner diameter of at least 175 mm and a maximum of 225 mm,
- A maximum of one bend of 90° or less may be applied in the sampling tunnel (i.e. downstream of the brake enclosure and upstream of the sampling plane),
- If a bend is applied in the sampling tunnel, the bending radius shall be at least two times the duct inner diameter,
- If a bend is applied in the sampling tunnel, a straight duct with a length of at least six times the duct diameter shall follow the bend before locating the sampling plane,
- If there is no bend in the sampling tunnel, a straight duct with a length of at least six times the duct diameter shall follow the exit of the enclosure before locating the sampling plane. Additionally, a straight duct with a length of at least two times the duct diameter shall follow the sampling plane before placing any flow disturbance [6].

The sampling plane is the vertical plane in the sampling tunnel where the inlet of the sampling probes is placed. There are two possibilities for the design of the sampling plane: a layout with three sampling probes and a layout with four sampling probes. Figure 3 illustrates the proper positioning of the PM and PN sampling probes for both the three and four sampling probes layout. The minimum specifications related to the positioning of the sampling probes are as follows:

- Sampling probes shall be equally spaced around the central longitudinal axis of the sampling tunnel with a minimum distance between them of 47,5 mm ($a_1 \geq 47.5$ mm),
- The minimum radial distance of the sampling probes from the tunnel wall (probe-to-duct distance) shall be 47.5 mm ($a_2 \geq 47.5$ mm).

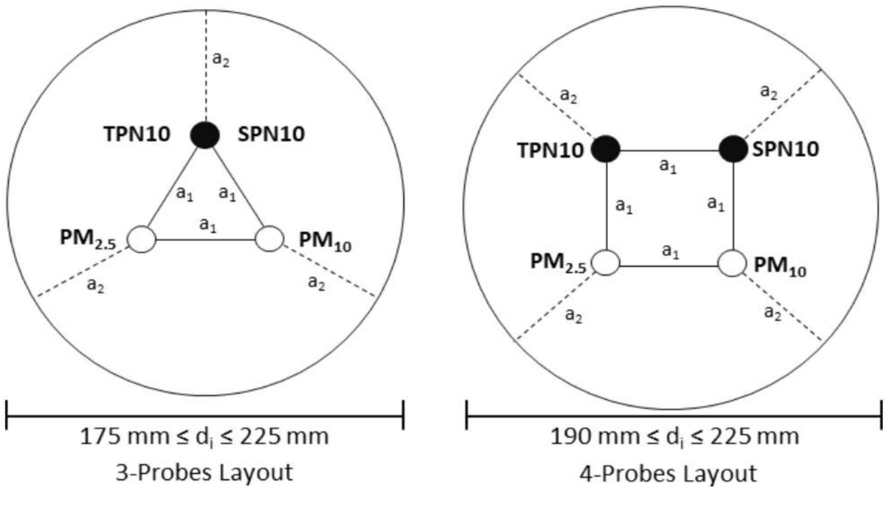

Fig. 3 Positioning of the PM and PN sampling probes in the tunnel [6]

Conclusion

This study presents the design requirements for the measurement of brake particle emissions. The harmonised approach integrates elements from existing standards and research practices to define a robust, repeatable, and technically sound measurement framework. Key parameters, including sampling methods, braking cycles, and environmental conditions have been standardised to reduce variability and improve cross-comparability between laboratories and test facilities.

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OPTIMIZATION OF THE PRODUCTION PROCESS USING VALUE STREAM MAPPING IN A SELECTED ENTERPRISE

Dariusz MICHALSKI – Marek MIZERÁK – Monika MICHALSKA

Abstract: This article demonstrates process optimization opportunities using value stream mapping, using a company as an example. Production planning in the analyzed company is primarily based on customer orders. In the case of increased production, the company's plan assumes "make-to-stock" production. This assortment is carefully selected and primarily concerns high-turnover products. To optimize the production process, the possibility of applying Lean Manufacturing principles to one of the manufacturing processes was analyzed. The execution times of individual operations in the process were measured, value stream maps were created, waste was identified, and necessary improvements were made to the value stream and operations themselves.
Keywords: Lean Manufacturing, flow mapping, optimization.

1. Mapping the value stream in the examined enterprise

To optimize the production process, an analysis was conducted to assess the potential application of Lean Manufacturing principles to one of the manufacturing processes. The execution times of individual operations within the process were measured, value stream maps were created, waste was identified, and necessary improvements were made to both the value stream and the operations themselves. The map was not created for all the components produced at the studied company. In this case, the focus was limited to a single product. The selected product was a radiator transport cart [4].

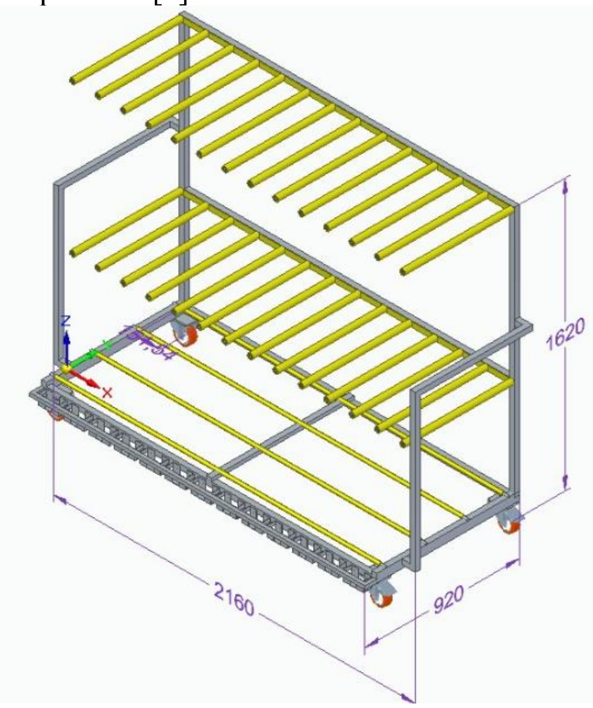

Fig.1. Construction of a trolley for transporting radiators.

The trolley's structure is made of 40x40x2 mm closed profiles. 17.23 m of profiles are required to manufacture one trolley. The separation arms are made of 30x2 mm diameter pipe. 18.2 m of pipe are required to manufacture the trolley. The trolley's structure is manufactured in a production process taking place on the company's premises. Cutting of the profiles and pipes is performed using CNC technology. Cutting the pipes and profiles takes one employee 40 minutes. This is performed in a work cell called "cutting." The finished materials are transported in a container to the next work cell, where welding is performed. Transport takes 5 minutes. Welding is performed using the MIG-MAG method. This is a time-consuming process, taking 330 minutes. After the finished frame and arm are prepared on a forklift, the product is transported to the next work cell, where grinding is performed. Transport takes 5 minutes. Grinding is intended to eliminate any irregularities in the previously made welds. This operation takes 30-40 minutes, depending on the weld finish. A maximum time of 40 minutes was assumed for this purpose. After grinding, the product is transported to a specially designated part of the production hall where painting is performed. Transport takes 5 minutes. The next step is preparation for painting. This operation takes 30 minutes. The next step is painting. Painting is performed using the powder coating method and takes 25 minutes. However, it should be noted that the drying time is 480 minutes. The trolleys remain in this station until drying. Once dry, they are transported to the final station. Transport takes 5 minutes. The final operation is the assembly of the wheels and polyurethane bushings for the separation arms. This is performed by two workers and takes 105 minutes. The total production time for one radiator transport cart is 1045 minutes, or approximately 17 hours and 40 minutes [2]. Based on the collected information, an as-is value stream map was created, as shown in Figure 2.

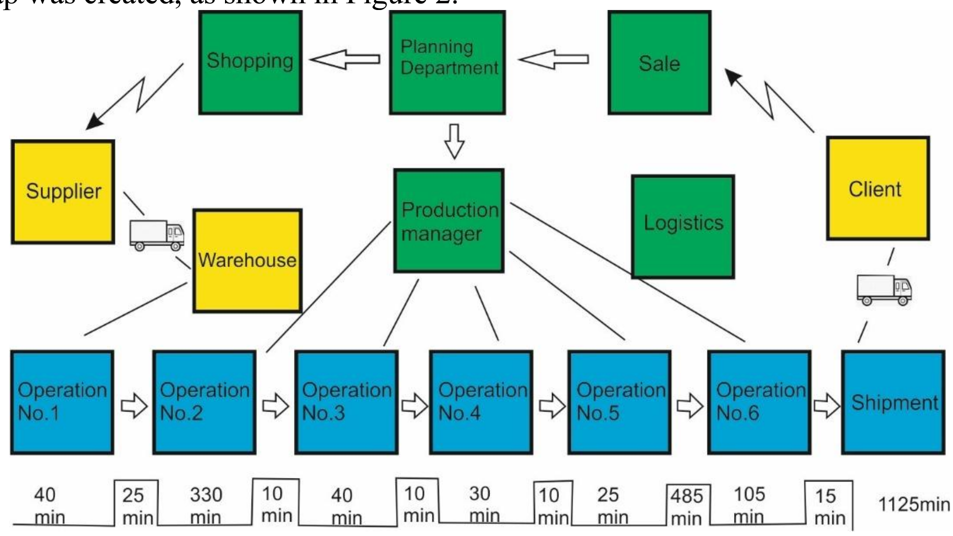

Fig.2. Current state map.

The upper part of the map shows the flow of information from the customer through the exchange of information within the company. The customer places an order and optionally submits a design to the Sales Department. From the Sales Department, the order is transferred to the Planning Department. This department analyzes the design provided by the customer or develops a design by the company's engineers. The Planning Department sends the demand for individual products that will comprise the product to the Purchasing Department, where the order is completed. Warehouse stock is used first. If materials are needed that are not in stock, they are ordered from suppliers. The lead time for individual items depends on the supplier's inventory [3].

The material flow is shown in the lower part of the map, from the supplier, through the production process, and finally to the customer (from left to right).

Table 1 presents the individual operations and their durations. A single-item flow occurs between operations, maintaining the first-in, first-out principle. According to this principle, items stored in the warehouse the longest are released first. Therefore, it should be noted that no in-process inventory accumulates between individual operations.

Tab.1. Production process and duration of individual operations.

Operation	Duration of operation [min]	Extra time
Cutting the material	40	35
Welding	330	10
Grinding	40	10
Preparation for painting	30	10
Painting	25	485
Installing the wheels and polyurethane bushings on the separation arms	105	15
Total operation time	**570**	**565**

The transit time, and therefore the total production time for the finished product, a radiator transport trolley, is 1135 minutes, or 18 hours and 55 minutes. Of this, 570 minutes is processing time, which adds value. This means that 50% of the product production time is spent on non-value-adding activities. These activities include transport between workstations (65 minutes in total), loading and removal of the cut material to the waste storage (20 minutes). Therefore, the non-added value of transporting and loading individual components onto the forklift amounts to 85 minutes.

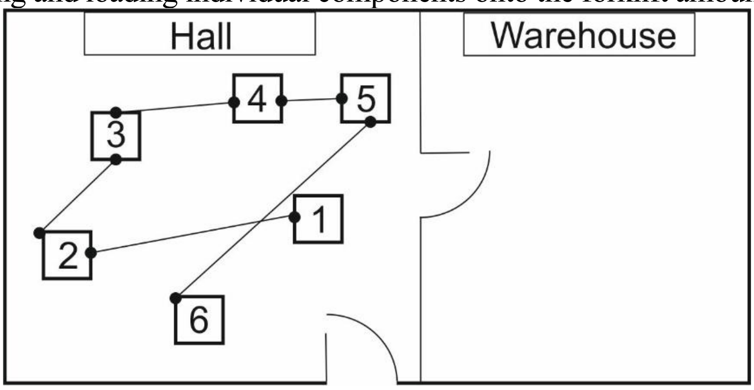

Fig.3. Existing layout of work centers.

In this case, the largest portion of non-value-added activities is the transport and loading of individual components between work centers, as well as drying the product after painting. The paint drying time, according to the manufacturer's recommendations, is 8 hours. Optimization is not possible in this respect. A workstation that can be optimized is the material cutting station. Currently, a semi-automatic saw designed for cutting pipes and rods is used. This requires operator control, which increases cutting time because changes to the material's parameters must be manually entered by the operator. Furthermore, after the job is completed, the operator must load and transport the cutting waste to a warehouse.

Analysis of the map indicates that transportation is a process contributing to waste. In the analyzed process, transportation is typically performed using a forklift. The total distance a semi-finished product must travel is 10-70 meters. This distance represents the distance of moving elements between subsequent stations, excluding transport associated with painting and drying.

The time required to transport individual elements is prolonged due to the poor layout of individual production cells and the use of an inappropriate means of transport.

2. Proposed changes to optimize the production process.

The analysis and identification of key activities that do not add value to products allow for the identification of any irregularities in the organization of processes at the studied enterprise. Suggested improvements are presented in Table 2.

Tab.2. Suggested improvements to the organization of processes in the production system at the studied enterprise.

Irregularity	Improving process organization
Chaos in the warehouse	Introducing Lean - 5S tools in the warehouse to eliminate the chaos that prevails there.
Work center improvement – material cutting	Purchase of an automatic saw
Excessive transportation	Introduction of a lean tool to optimize in-plant transport
Incorrect arrangement of production process stations	Redesigning the layout of production stations
Lack of standard work procedures in the company	Establishing standard procedures for all operations

Among the proposals for optimizing the operation of the production department, the implementation of an integrated computer system is proposed, which will streamline the production department and key areas of company management. Implementing an integrated IT system will improve information flow. In turn, standardizing all operations within the company will ensure waste-free processes. Implementing such changes reduces waiting times related to, for example, machine failures or downtime. Standardization, combined with specialized training, allows for the improvement of employee qualifications, allowing for the replacement of one employee in the event of an absence. Currently, production uses a semi-automatic pipe and rod saw for cutting, which requires operator supervision. When parameters are changed, the operator must enter them each time. A proposed solution is to purchase an automatic, universal pipe and rod saw. This allows all settings to be adjusted automatically when changing production, along with changes in cross-section. One of the features of such a saw is automatic control of all axes, allowing for continuous production without dead time [7].

The non-added value in this case is transportation. The production of one radiator transport trolley takes a total of 85 minutes, including loading the semi-finished product, transporting it to the next work center, and unloading it. It's important to note that currently, semi-finished products are transported by forklift. To optimize the production process, it's important to shorten transportation times. The proposal involves using specially designed trolleys onto which cut rods would be loaded at the first station. Each shelf of such a trolley could hold rods of different lengths. The material would be delivered to the second station. After welding, the operator would load the welded components onto the trolley, which would then be sent for grinding. The semi-finished product would then be transported on the same trolley for preparation for painting, painting, and to the station where wheels and other components are assembled. A single trolley would be assigned to each product in this category, reducing transportation time. It's worth noting that the company has the ability to design and manufacture such a trolley itself, which reduces its cost. Another proposed change is the rational arrangement of production stations in a U-shape. Currently, the production floor is chaotic. Stations are not properly arranged. Transport of semi-finished products takes longer because some work centers are far apart, even though the activities within them are performed consecutively. The proposal for a new arrangement of workstations is presented in Figure 4.

Another suggested tool for optimizing the production process is the implementation of the 5S system, which will allow for the creation and maintenance of a well-organized and clean workstation. In this area, it is crucial that each workstation contains only the equipment and tools necessary for a given process. It is crucial that employees maintain a tidy workstation and regularly inspect the tools they use. Maintaining a clean and safe workstation, as well as maintaining and improving machine efficiency, increases safety and reduces the incidence of machine breakdowns [5, 6]. Figure 5 presents the value stream map after the changes.

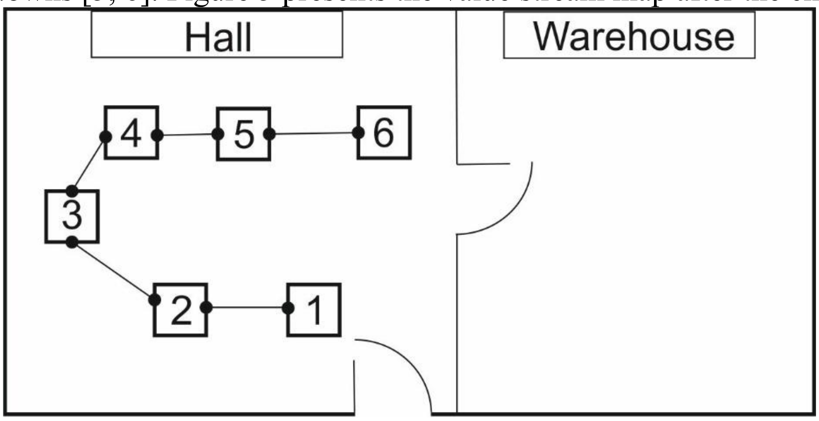

Fig.4. Proposed layout of workstations.

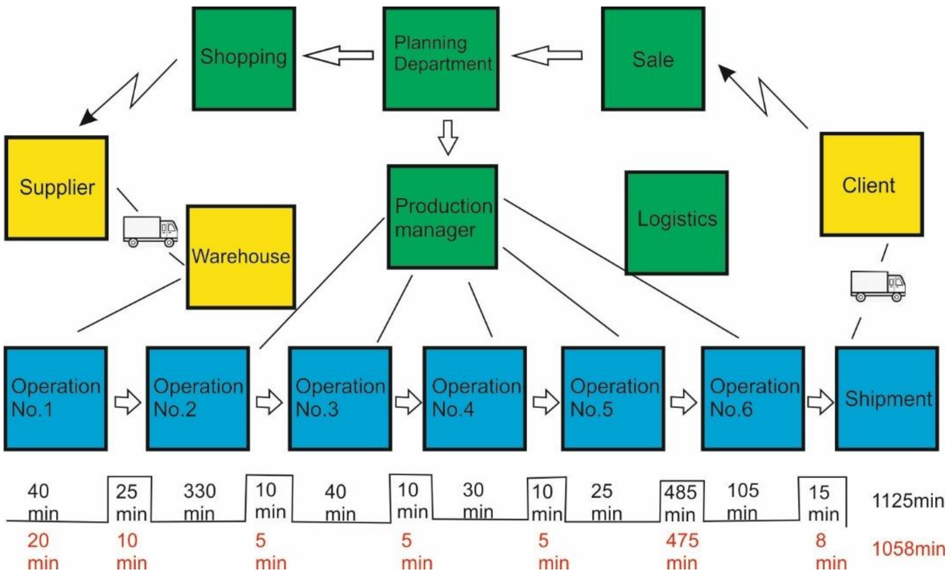

Fig.5. Value stream map after the proposed changes.

Analysis of the value stream map after the proposed changes indicates that the total production time of the radiator trolley can be reduced from 1125 minutes to 1058 minutes, i.e. it can be shortened by 67 minutes.

Tab. 3. Production process and duration of individual operations after changes.

Operation	Duration of operation [min]	Extra time
Cutting the material	20	10
Welding	330	5
Grinding	40	5
Preparation for painting	30	5
Painting	25	475
Installing the wheels and polyurethane bushings on the separation arms	105	8
Total operation time	**550**	**508**

Optimizing the production department using Lean Production tools will primarily focus on productivity and profitability, improving financial performance by reducing production costs, and contributing to greater customer satisfaction. Lean tools contribute to flexibility in production control, reducing defects and poor quality errors through continuous monitoring, and increasing employee discipline. Other benefits include the rational use of company resources and more efficient management of machinery [1].

Conclusions

The main aim of the article was to analyze and improve the production process by using Lean Manufacturing tools in order to reduce waste occurring in the examined company and shorten the time of customer order fulfillment. Value stream mapping allows you to identify gaps in information flow that prevent or delay subsequent stages of order fulfillment. It also allows you to increase bottleneck capacity, increase stream productivity, and reduce production costs. This tool also shows where breakdowns and unplanned downtime can be eliminated, and work can be standardized to maintain the lowest possible inventory levels. The applied value stream mapping method revealed the problem areas facing the studied company. Reorganizing the workstation layout eliminated unnecessary transport operations and freed up space on the production floor. The U-shaped arrangement is more ergonomic, facilitates communication between employees, and eliminates excessive transport between workstations. Furthermore, the purchase of a new, automatic pipe and rod cutting machine will shorten work time at this stage of production, maintain high production quality, and eliminate the added value of employee intervention each time cutting parameters are changed. Analysis of the presented case demonstrates the significant potential and demand for Lean Manufacturing solutions, even in small businesses. Applying this philosophy requires overcoming barriers related primarily to distrust of innovative solutions in organizational and management.

Acknowledgments

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UTILIZATION OF MICROSOFT POWER BI FOR IMPROVING DECISION-MAKING TROUGH INTERACTIVE DASHBOARD

Dominika SUKOPOVÁ – Milan FIĽO –Lenka LEŠČINKÁ –Jaroslava JANEKOVÁ

Abstract: The article focuses on the implementation of Microsoft Power BI as a tool for creating interactive dashboards to support data-driven decision-making. The study describes the process of data preparation, metric definition, and visualization through Power BI dashboards. Four key dashboards were developed: KPI Dashboard, Cost Dashboard, Revenue Dashboard, and Department Overview Dashboard. These dashboards enable real-time insights and enhance the managerial decision-making process by transforming raw data into meaningful visual representations. The article demonstrates how Power BI contributes to better business performance monitoring and provides flexibility in analysing financial and operational indicators.
Keywords: Power BI, Dashboards, Business Intelligence, Data Visualization, Decision-Making

Introduction

In the era of digital transformation, businesses are increasingly reliant on data to drive strategic decisions. Business Intelligence (BI) tools have become indispensable in collecting, analyzing, and visualizing large volumes of data. Among these tools, Microsoft Power BI stands out for its flexibility, integration capabilities, and ease of use. The main objective of this paper is to present the application of Power BI in the development of interactive dashboards that support managerial decision-making processes.
Business Intelligence (BI) is a process of transforming raw data into actionable information to support business decisions. According to Gartner, BI combines data mining, process analysis, performance benchmarking, and descriptive analytics. Visualization tools, such as dashboards, play a critical role in presenting key performance indicators (KPIs) and trends in a clear and interactive format. Power BI, developed by Microsoft, allows users to connect to multiple data sources and create real-time reports with interactive filters and data models.

Methodology

The research methodology involved several stages: data collection, cleaning, transformation, and visualization. Power Query was used for data preparation, while DAX (Data Analysis Expressions) was utilized to create custom metrics. Dashboards were designed to provide an overview of financial and operational indicators through interactive visuals. Each dashboard serves a specific purpose in monitoring company performance and improving decision-making efficiency.
The process started with collecting company data from internal databases and Excel spreadsheets. These datasets contained financial indicators, cost structures, and departmental performance measures. In the next stage, Power Query was used to clean and transform the data to ensure accuracy and compatibility across all tables. Using DAX, calculated measures were created to evaluate key performance indicators (KPIs), profitability ratios, and cost efficiency.
Once the data model was complete, visual elements were designed in Power BI to enable intuitive navigation and filtering. The dashboards were tested by management to verify clarity, accuracy, and usability in practical decision-making scenarios.

The entire process is illustrated in Fig. 1, which presents the workflow of the research methodology.

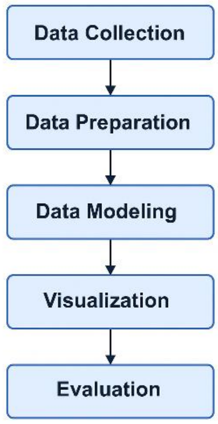

Fig. 1 Research Methodology Workflow

Results and Discussion

Four dashboards were developed within Power BI to illustrate the analytical and decision-support capabilities of the tool:

- KPI Dashboard – provides a summary of key performance indicators, enabling managers to track trends over time and monitor goal achievement.
- Cost Dashboard – focuses on cost structure analysis, allowing comparisons across departments and time periods.
- Revenue Dashboard – visualizes revenue distribution and highlights main sources of income.
- Department Overview Dashboard – offers a comparative analysis of departmental performance.

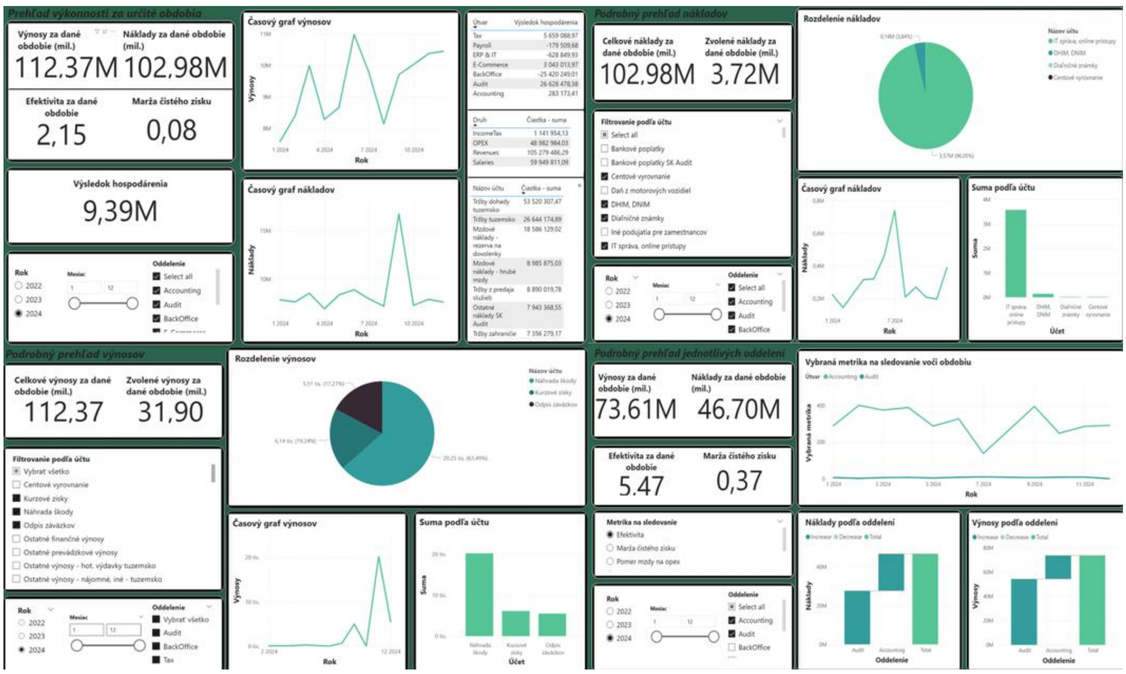

Fig. 2 Overview of Developed Power BI Dashboards

Note: The dashboards are presented in the Slovak language due to company-specific requirements for internal reporting.

Conclusion

The implementation of Microsoft Power BI has proven to be an effective tool for enhancing data-driven decision-making in a business environment. Through the development of interactive dashboards, it is possible to transform large and complex datasets into clear, understandable, and actionable insights. The four developed dashboards — KPI, Cost, Revenue, and Department Overview — provide managers with real-time information, allowing them to identify trends, monitor performance, and respond quickly to changes in key business indicators.

The study demonstrated that Power BI enables not only visualization but also integration, automation, and continuous updating of data, which significantly improves the efficiency of business analysis. The flexibility of the tool allows its application across different organizational levels and areas.

In the future, the integration of predictive analytics, artificial intelligence, and automated reporting within Power BI could further expand its potential in supporting strategic management and decision-making processes.

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VEGA 1/0219/23 – Empirical research of the relation of implementation of advanced technologies and sustainable behavior of manufacturing companies in Slovakia.

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SYNERGY OF LEAN MANUFACTURING AND INDUSTRY 4.0 IN STREAMLINING THE ASSEMBLY PROCESS

Marek MIZERÁK – Daniel DĘBOWSKI– Jozef TROJAN – Dariusz MICHALSKI

Abstract: This paper explores the integration of Lean Manufacturing principles with Industry 4.0 technologies to optimize production processes. The study focuses on the P10 assembly station, where a detailed analysis of material flow and time measurements was conducted using the MTM (Methods-Time Measurement) method. The goal was to identify waste, improve cycle times, and enhance overall efficiency. The layout was designed using nanoCAD software, and the results demonstrate measurable improvements in productivity and cost savings. The findings support the synergy between traditional lean tools and modern digital solutions, offering a practical framework for smart manufacturing transformation.
Keywords: Lean Manufacturing, Industry 4.0, MTM analysis.

Introduction

The origins of the Lean Manufacturing concept date back to the 1950s and 1960s, when it was developed by the Japanese company Toyota as part of the Toyota Production System (TPS) methodology. Its creators were engineers Taiichi Ohno and Shigeo Shingo, who laid the foundations of an approach focused on efficiently satisfying customer needs by producing exactly what is required.

The goal of lean manufacturing is to achieve production in the shortest possible time and at the lowest possible cost, while these efforts must not compromise product quality or customer satisfaction. In this sense, the well-known slogan "Our customer, our master", already used in the workshops of Tomáš Bata, can be considered the motto of the entire concept.

Lean manufacturing is particularly applicable in a mass production environment, where high flexibility and low investment costs are required. The basic tool for achieving these goals is the elimination of waste – that is, all activities and resources (material, personnel or information) that increase costs but do not bring any added value to the customer. In Japanese terminology, this phenomenon is called MUDA [1][2].

The Lean Manufacturing methodology changes the equation as follows:

$$\text{Cost} + \text{Profit} = \text{Price} \rightarrow \text{Price} - \text{Cost} = \text{Profit}.$$

The result of modifying this equation is that in the first case, the customer pays for errors occurring during the transformation process, while in the second case, errors in the process represent costs that reduce the final profit of the producer and therefore do not affect the customer. By applying this philosophy, companies strive to become competitive and affordable for their customers, while providing them with the maximum possible quality.

Lean Manufacturing and INDUSTRY 4.0

In recent decades, industry has undergone a significant transformation, leading from traditional mass production methods to Lean Manufacturing methods. Lean manufacturing emphasizes efficient use of resources and increased productivity through a wide range of optimization tools. However, with the advent of new innovative technologies and the development of the Internet of Things (IoT), we can talk about a new era of manufacturing, namely the era of smart manufacturing and smart factories.

Smart factories use advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, or cloud computing to create a fully integrated and automated production process. Smart factories offer several advantages over Lean Manufacturing, such as real-time data analysis, remote monitoring of the production process, or dynamic production planning. Smart manufacturing allows manufacturers to optimize the production process by minimizing downtime, reducing waste, and improving product quality [3].

Currently, the field of optimization of production systems requires the synergy of traditional Lean Manufacturing methods and modern Industry 4.0 tools. This combination makes it possible to achieve the highest possible efficiency of the production process and gain a competitive advantage. While lean manufacturing tools are used to eliminate waste and optimize material flows, Industry 4.0 tools help in collecting and analyzing data in real time. This combination supports increasing production efficiency, increasing production flexibility and strengthening competitiveness in today's dynamically changing and evolving market of products and services [4][5].

The image below presents a visual interpretation and connections of Lean Manufacturing and Industry 4.0 tools, which in their joint synergy create the imaginary concept of Lean 4.0.

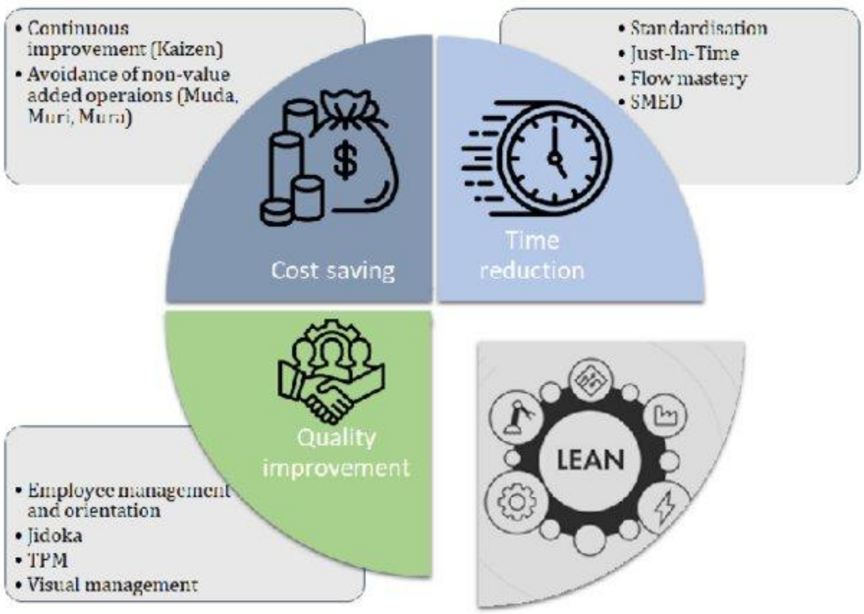

Fig. 1 Lean manufacturing concepts

Production station P10
The aim of this article is to perform a thorough analysis of the current state of the production line, identify forms of waste in the process and propose optimization solutions that will streamline the transformation process on the line. The resulting solution should bring financial savings and increase the output of the production line.

The layout of the production line along with the marking of the material flow is shown in the following figure. The layout was created in nanoCAD software.

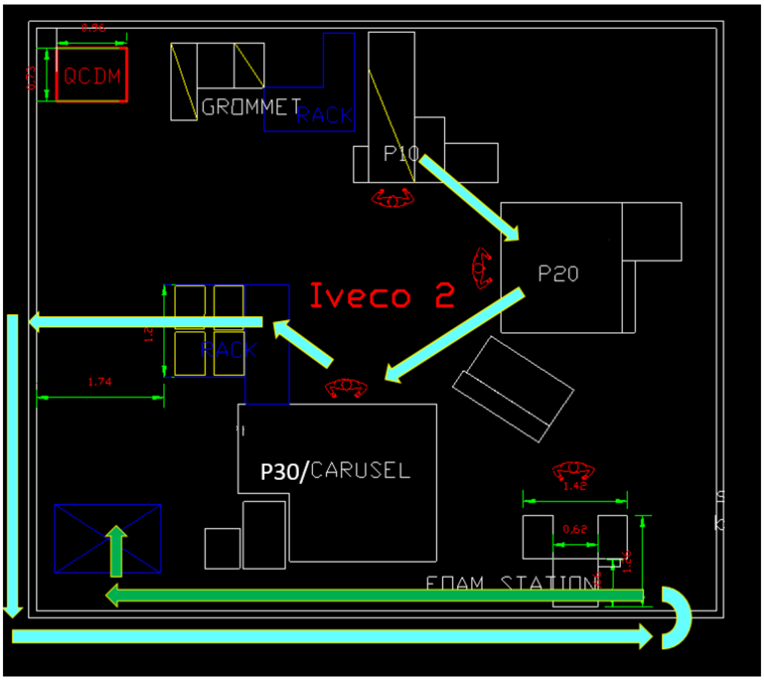

Fig. 2 Current production line layout and material flow representation

nanoCAD Software
nanoCAD software is designed for creating 2D projects and creating drawing documentation. The software is used by engineers, architects and designers. The software provides a wide range of tools for precise drawing and editing of geometric shapes, such as lines, polygons, arcs or circles. The user-friendly environment is suitable for ordinary users of CAD software and also provides support for common output formats, thus enabling collaboration and sharing of projects. NanoCAD includes functions such as blocks, layers or object properties. Its affordability and ease of use make it a widely used and competitive solution for the work of designers in any field [6].
In the company, this software is mainly used for managing the layout of the factory's production and administrative spaces. However, it also has its uses in creating simple drawing documentation.

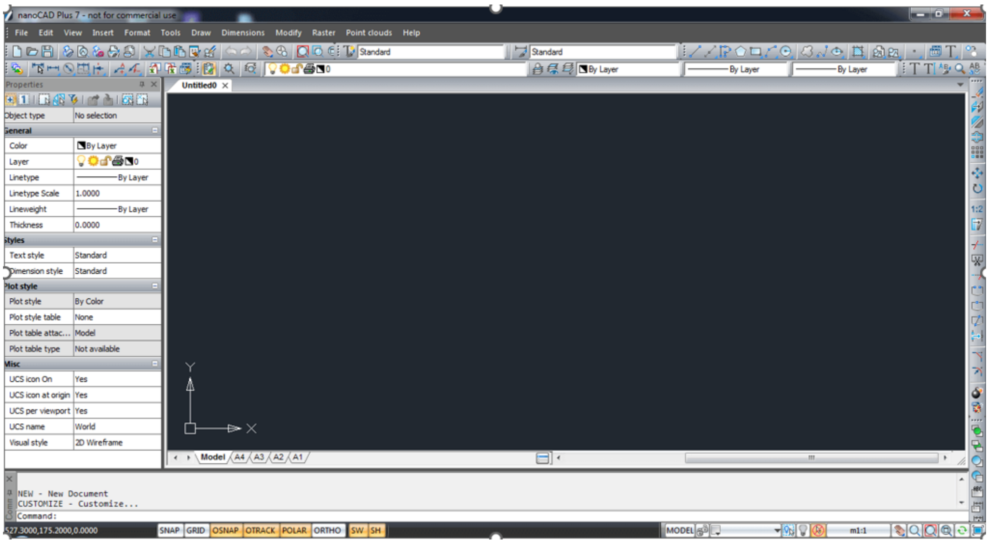

Fig. 3 Používateľské prostredie softvéru nanoCAD [vlastné spracovanie]

Material flow of the production line

Workstation P10

This is a workplace with one operator, where the assembly of the kinematic (CIN component) and resistance (RET component) parts of the internal door lock is carried out. It is the first workstation of each manufactured reference. The line is supplied from the rear and all the necessary components for assembly are stored in plastic boxes and tubes, which the operator replaces and replenishes as needed. The supply of components to the line is provided by a linefeeder.

The assembly itself (by riveting) takes place in the machine nest, the operator's task is to insert the connecting components into the kinematic -CIN and resistance -RET parts and insert the pieces into the nest in which the assembly is taking place. Before assembly, the operator checks the type of CIN and RET component used. After assembly, a visual inspection of the assembly and the placement of the OK piece into the rail follows. All parts of the workplace are fixed (racks, nest). The racks are designed on the principle of gravity slides.

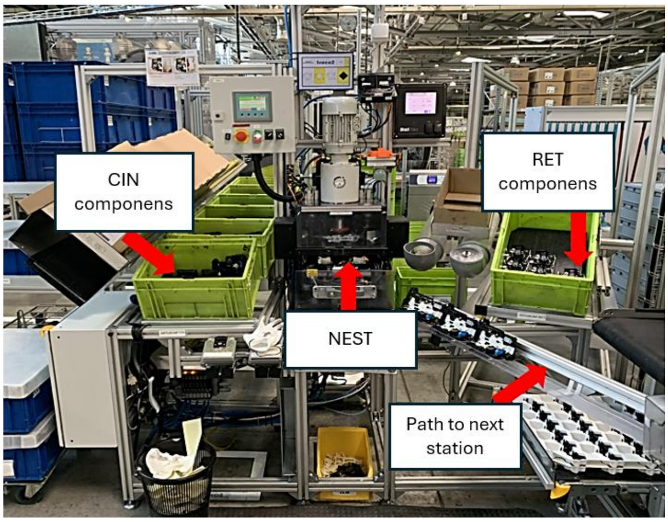

Fig. 3 Production station P10

Measuring production times of workstations on the line

The MTM method – Methods-Time Measurement represents an analytical approach used to determine time standards for individual operations in the production process. Its main goal is to create standardized work procedures, time standards and production plans. In practice, it is used to accurately determine the duration of work through a detailed breakdown of work activities into elementary operations. Time studies, supplemented with information on equipment performance, subsequently form the basis for capacity calculations related, for example, to the consumption of human labor, material or to determining the maximum production capacity of the process. This method is universally applicable in various industrial sectors with the aim of increasing time efficiency and minimizing losses [7].

In the studied company, MTM is one of the most frequently used analytical tools for evaluating production processes. Despite its conceptual simplicity, its application requires detailed knowledge of processes and compliance with standardized measurement conditions. When evaluating production cycles, the time consumption associated with:
- production equipment,
- workers,
- workplace,
- product is monitored.

A quality time study requires measurement under precisely defined conditions. If a worker is involved in the measurement, it is essential that he or she follows the prescribed work procedure. In case of non-compliance, the worker must be retrained and the measurement repeated after the time required to master the required procedure. At the same time, an appropriate level of worker training (so-called polyvalence) must be ensured. Within the company's internal standards, four levels of training are distinguished:
- Level 1 – the operator works only under the supervision of a trainer,
- Level 2 – the operator is capable of independent work, but not in line rhythm,
- Level 3 – the operator works independently in line rhythm,
- Level 4 – the operator is capable of training other workers.

When analyzing standard activities, only operators with a training level of at least 3 are considered. It is also necessary to ensure standard operation of the equipment and an adequate number of workers operating the process under study.

The measurement procedure can be summarized in the following steps:

Defining the measurement object according to the purpose (e.g. line balancing, analysis of deviations between workers, etc.),

Initial observation of the process in order to verify compliance with work instructions and identify possible abnormalities, Elimination of identified deficiencies, or retraining of workers,

Measurement of time data using stopwatches (mostly discontinuously, due to possible external influences, such as malfunctions or the presence of non-standard persons in the workplace),

Recording data in a form (usually in MS Excel),

Evaluation of measured results and formulation of proposed measures.

To ensure the relevance of the results, each measurement must be repeated at least 20 times. It is also necessary to take into account operations that are not performed in every cycle, but only at certain intervals in the process. A typical example is the packaging of a box of finished products, which is performed only in every tenth cycle, since one box contains 10 pieces of products. In such a case, it is appropriate to measure 18 cycles without packaging and 2 cycles with packaging. Adherence to this principle is essential, because if we recorded, for example, three packaging operations in 20 cycles, the resulting average time would be incorrectly increased and would not represent the real value. For this reason, not only the accuracy of the measurement itself is crucial, but also thorough initial observation and detailed knowledge of the process under study [8][9].
The form for processing measurement data contains, in addition to the average value, the lowest measured value and other indicators, such as KOSU or hourly and shift capacity of the process. KOSU is a productivity indicator, which is calculated as follows:

$$KOSU = \frac{(Available\ time - Plnanned\ breaks) * number\ of\ emloyees}{Production\ volume}$$

Tab. 1 Technologies as initiative to a change

station	P10
work cycle 1 [s]	23,3
work cycle 2 [s]	22,9
work cycle 3 [s]	24,3
work cycle4 [s]	23,9
work cycle 5 [s]	22,0
work cycle 6 [s]	23,2
work cycle 7 [s]	22,8
work cycle8 [s]	23,3
work cycle 9 [s]	23,6
work cycle 10 [s]	22,2
work cycle 11 [s]	23,5
work cycle 12 [s]	22,0
work cycle 13 [s]	22,7
work cycle14 [s]	23,1
work cycle 15 [s]	23,2
work cycle 16 [s]	23,8
work cycle 17 [s]	22,9
work cycle 18 [s]	23,2
work cycle19 [s]	24,7
work cycle 20 [s]	22,3
Average time [s]	23,1
KOSU	69
Shift capacity [ks]	1129

Conclusion

In conclusion, it can be stated that the connection of traditional Lean Manufacturing tools with modern Industry 4.0 technologies represents an effective approach to optimizing production processes. The analysis of the P10 workplace using the MTM method made it possible to identify specific forms of waste and propose measures leading to increased productivity and reduced costs. The results confirm that the combination of theoretical knowledge with practical applications in the form of digital tools brings real improvements in production. This approach can serve as a model for other production lines as part of the transformation of companies into intelligent manufacturing systems.

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OPTIMIZATION OF ORDER PROCESSING AND DELIVERY WORKFLOW IN AVIATION SERVICE CENTER USING DIGITAL SIMULATION TOOLS

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Abstract: This study optimizes the order processing and delivery workflow in an aircraft Component Service Center using Tecnomatix Plant Simulation 2302. A discrete-event digital twin models the full logistics chain—from order intake to carrier release—for wheels and brakes. Simulation of 130 monthly orders reveals bottlenecks at brake maintenance and certification stages, with utilization exceeding 85% and mean cycle times of 4 days 34 min (brakes) vs. 3 days 18 h (wheels). Downstream packaging remains underutilized due to upstream delays. Quantitative outputs validate throughput accuracy and identify targeted improvements: resource reallocation and task parallelization. Results demonstrate a potential 18% reduction in lead time without structural changes. The approach provides a low-risk, data-driven framework for MRO logistics optimization under Industry 4.0.

Keywords: Aircraft maintenance, logistics optimization, Tecnomatix Plant Simulation, order management, process efficiency.

Introduction

The effectiveness of maintenance operations within the aviation industry depends largely on the precision, coordination, and reliability of internal logistics processes. Among these, the handling of maintenance orders — from their reception to the final delivery of serviced components — represents one of the most critical elements influencing overall operational efficiency. Aircraft component maintenance requires not only technical excellence but also a well-structured logistical system capable of managing the flow of materials, documentation, and information without delay or error. Any inefficiency in this chain can directly affect aircraft availability, maintenance turnaround times, and customer satisfaction.

In recent years, the aviation maintenance, repair, and overhaul (MRO) sector has faced increasing pressure to enhance productivity while maintaining strict regulatory compliance. The complexity of logistics operations, combined with high safety requirements and fluctuating workloads, creates significant challenges for process optimization. Traditional methods based solely on experience or manual coordination are often insufficient to manage such dynamic systems effectively. Therefore, modern MRO organizations are progressively adopting digital tools that allow for the simulation and evaluation of logistical processes before implementing changes in real operation [1,2].

The motivation for this study arose from the need to better understand and optimize the internal workflow of an aircraft Aviation Service Center, particularly concerning the reception, processing, and delivery of customer orders. The observed processes, though well established, exhibit certain limitations in efficiency and transparency that may influence service lead times. The aim of the research is to analyze these operations using Tecnomatix Plant Simulation 2302, a digital modeling environment that enables the creation of a virtual representation of the workflow. Through simulation, it becomes possible to identify potential bottlenecks, assess

system performance, and propose improvements grounded in quantitative data rather than assumptions [3].
This article contributes to the ongoing discussion on the digital transformation of logistics systems within the aviation maintenance domain. By integrating simulation tools into the analysis of order processing, the study demonstrates how digital modeling can support decision-making, improve resource allocation, and strengthen the reliability of service delivery. The presented results also serve as a methodological reference for other organizations seeking to implement similar approaches to process analysis and optimization.
The remainder of this paper is structured as follows: Section 2 presents the methodology and description of the simulation environment; Section 3 outlines the developed model and results; Section 4 discusses the findings and implications for practice; and Section 5 concludes with recommendations for future research and implementation [4].

Materials and Methods

Process Overview

The analyzed logistics process in the Aviation Service Center represents a closed operational chain that connects customer interaction, maintenance execution, and final delivery. The system is based on the continuous circulation of components, documentation, and information among several specialized workstations. Each order corresponds to a specific component — typically aircraft wheels or brakes — that must undergo inspection, repair or overhaul, and subsequent verification before release to service [5].
The workflow begins with order reception and registration in the AMOS (Aircraft Maintenance Operating System). This platform functions as the central data repository, ensuring traceability and integration between technical and logistical departments. Each order entry includes essential details such as component identification numbers, maintenance requirements, delivery deadlines, and previous service history.
After registration, the components proceed to inspection and assignment. The inspection phase determines the condition of the incoming item and defines the necessary maintenance scope. Based on these findings, each component is directed to the appropriate specialized workstation — either for standard repair or complete overhaul. This stage is critical because it influences subsequent resource allocation and process timing.
The maintenance and overhaul operations are performed in accordance with aviation maintenance standards and manufacturer documentation. All technical actions are logged into the AMOS system to maintain a consistent digital record. Upon completion, the components undergo certification and quality verification, confirming their conformity with regulatory and safety requirements. This stage is a mandatory part of the MRO workflow, as only certified components can be released for use in aircraft systems.
In the end of the process, the components are transferred to packaging and dispatch, where they are prepared for transport to the customer or to another maintenance site. This final phase includes documentation verification, packaging in accordance with safety standards, and order closure in the information system. The overall process structure ensures full traceability of each order and provides data suitable for digital modeling and simulation.

Simulation Environment

To obtain a detailed understanding of the workflow dynamics, the process was digitally modeled and analyzed using Tecnomatix Plant Simulation, developed by Siemens Digital Industries. This tool allows for the creation of discrete-event simulation models representing manufacturing and logistics systems with high accuracy [6].

The model was first constructed in a 2D environment, which facilitated the definition of process logic, flow control, and data connections between elements. Subsequently, a 3D visualization was developed to enhance spatial interpretation and to illustrate the interrelation between workstations. This dual-layer design supports both analytical precision and intuitive comprehension of the system's behavior.
The input parameters for the simulation were derived from the operational characteristics of the Aviation Service Center. The average monthly inflow of orders was set at 130 units, reflecting the real throughput under standard operational conditions. Each workstation — including the wheel maintenance station, brake maintenance station, NDT (Non-Destructive Testing) section, certification unit, and packaging area — was assigned process-specific cycle times based on empirical observations and standard maintenance procedures [7, 8].
During the simulation, data were collected to evaluate resource utilization, waiting times, and total order completion times. These performance indicators provided the basis for identifying system bottlenecks and assessing the efficiency of workflow coordination. The simulation was executed in multiple iterations to ensure model stability and consistency of results [9, 10].
The use of Tecnomatix Plant Simulation enabled a quantitative and visual analysis of the internal logistics network, offering a decision-support tool for improving process balance, scheduling, and overall operational performance [9].

Simulation Model and Results

Workflow Representation

The developed simulation model reflects the complete sequence of operations carried out within the Aviation Service Center, encompassing all stages from initial order reception to final dispatch. The general process flow can be expressed as in the figure 1.

Figure 1. Schematic representation of the simulated order processing and delivery workflow

Each phase in the model represents a specific segment of the internal logistics system. Orders generated at the inflow point enter a controlled distribution mechanism, where they are classified according to component type and service requirements. The flow control module directs each order either to the wheel maintenance or brake maintenance workstation, ensuring that the processing capacity is aligned with the technical specialization of the work area.
After completion of maintenance tasks, the components proceed to the Non-Destructive Testing (NDT) stage, where integrity checks are simulated to verify compliance with airworthiness criteria. Components that successfully pass the NDT inspection are routed to the certification unit, where the digital model simulates administrative and technical verification procedures corresponding to real-world documentation and release processes.
The final steps include packaging and dispatch, representing the logistical preparation of serviced components for delivery. These stages were modeled with specific handling times and transport readiness checks to replicate the real operational conditions. The structure of the workflow, along with defined process interconnections, allows the simulation to reproduce realistic order dynamics and to monitor performance indicators across the entire chain. The simulation in a 2D environment can be seen in figure 2.

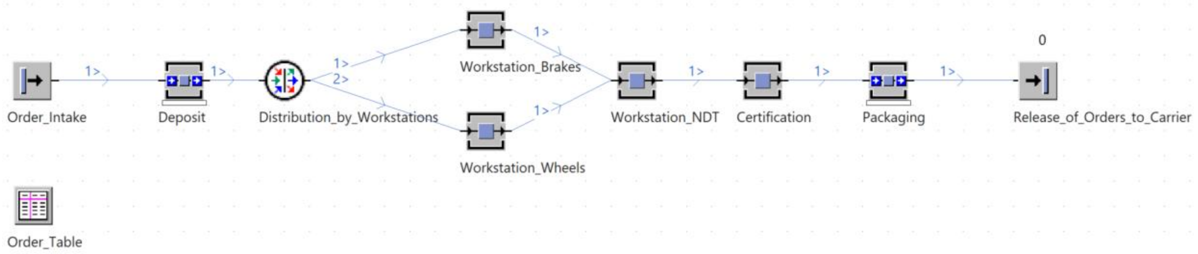

Figure 2. 2D visualization of the digital twin simulation in Plant Simulation

Performance Statistics

Quantitative data obtained from the simulation runs provide a detailed overview of the system's operational efficiency. The primary focus was placed on three key performance parameters:

- Average process time per component,
- Station utilization levels,
- Occurrence of idle or waiting periods within the process flow.

The results indicated that the average order cycle time remained consistent with the expected monthly throughput, confirming that the simulation accurately replicated the real process rhythm. However, analysis of internal timing revealed non-uniform workload distribution between workstations. The brake maintenance and certification stages exhibited the longest cycle times and the highest degree of utilization, which points to potential capacity limitations or scheduling imbalances.

In contrast, the packaging and dispatch areas demonstrated shorter processing times and periodic idle intervals, suggesting that upstream delays reduce the continuity of their operation. The simulation also showed moderate waiting periods before the NDT stage, typically resulting from asynchronous completion of maintenance tasks. These observations highlight the areas where optimization measures — such as reallocation of human resources or parallel task sequencing — could lead to measurable reductions in turnaround time.

Overall, the statistical evaluation confirmed that process efficiency is constrained primarily by the limited capacity of specialized stations rather than by systemic design flaws. Addressing these local bottlenecks could improve total throughput without the need for major structural changes.

Visualization and Analysis

The visualization capabilities of Tecnomatix Plant Simulation were essential for interpreting the process behavior beyond numerical data. The 2D model provided a logical overview of process connections, while the 3D representation offered an intuitive depiction of spatial and temporal interactions among workstations [11].

Through animated visualization, it was possible to observe the movement of orders, the accumulation of components in queues, and the synchronization between workstations. The 3D environment highlighted specific congestion areas, particularly in the transition from maintenance to certification, where several orders tended to accumulate during peak operational loads [12].

Statistical outputs generated by the software — including cycle-time distribution graphs, station utilization charts, and process delay histograms — enabled a comprehensive quantitative evaluation. These tools facilitated comparison of alternative scenarios and supported the identification of critical time losses. The combination of numerical and visual results provided a well-rounded understanding of the process, serving as a solid foundation for proposing optimization strategies in subsequent stages of analysis.

Resource utilization breakdown across all workstations in the simulated Aviation Service Center is showen in the figure 3. The stacked bar chart (left) shows the proportion of time each station spends in Working (green), Waiting (yellow), Blocked (gray), and other states. The Workstation_Brakes exhibits the highest working fraction (~70%), confirming it as the primary capacity bottleneck. The occupancy chart (right) further illustrates near-full utilization of Brakes and Certification (red line near 100%), while Packaging and Deposit remain underutilized.

Figure 3. Resource utilization and Occupancy across workstations

The table in Figure 4 shows the total volume of orders transferred to the carrier. 130 components were manufactured per month (57 brakes, 73 wheels). This result directly corresponds to the observed operational inflow, confirming the compliance of the model simulation with the actual volumes and distribution of components.

Object	All Types	Brakes	Wheels
Release_of_Orders_to_Carrier	130	57	73

Part Types which the Drain Deleted

Figure 4. Simulated monthly throughput at final release stage

The table in Figure 5 shows comparative statistical table of processing durations from order intake to carrier release. Brakes exhibit a mean life time of 4 days 34 minutes and exit at 17:17 on average, compared to 3 days 18 hours and 14:13 for wheels. Daily throughput rates (1.31 brakes vs. 1.68 wheels) further underscore the capacity constraint in brake-related operations.

Release_of_Orders_to_Carrier	Life Time				Exit Time				Throughput		
	Mean Value	Standard Deviation	Minimum	Maximum	Mean Value	Standard Deviation	Minimum	Maximum	Total	Per Hour	Per Day
Brakes	4:00:34:44.2105	3:10:43.9596	3:01:00:00.0000	4:01:00:00.0000	17:17:08.5714	9:44:29.7472	8:00:00.0000	2:00:00:00.0000	57	0.054755043	1.314121
Wheels	3:18:05:45.2055	19:50:07.9770	9:00:00.0000	4:01:00:00.0000	14:13:20.0000	8:30:55.7074	8:00:00.0000	1:16:00:00.0000	73	0.07012488	1.6829971

Figure 5. Life cycle and Exit time statistics for brakes and wheels

These results collectively validate the presence of localized bottlenecks—particularly at Workstation_Brakes and Certification—while downstream stages such as packaging remain underutilized due to upstream delays. The quantitative evidence supports targeted optimization strategies without requiring structural overhaul.

Conclusion

The simulation results indicate that the Aviation Service Center’s internal logistics largely function as intended but are constrained by localized capacity limitations, notably at the brake repair and certification stages. This pattern — where specialized stations become throughput bottlenecks while downstream stations remain underutilized — aligns with findings from other maintenance-focused simulation studies that emphasize the importance of balancing specialized resources and buffering strategies to improve flow.

From an operational standpoint, the study demonstrates three practical advantages of applying discrete-event simulation in an MRO context. First, it permits quantitative identification of bottlenecks and waiting-time sources without interrupting live operations, enabling low-risk evaluation of corrective measures. Second, it supports resource-allocation experiments (e.g., adding temporary capacity or re-sequencing tasks) to estimate their likely impact on throughput before committing capital or personnel. Third, visualization of flows in 3D improves stakeholder understanding and communication of where and why delays occur. These three benefits are consistent with documented industrial applications of Tecnomatix and similar tools in production and logistics optimization.

The simulation provided a clear, data-driven view of internal logistics and exposed workload imbalances concentrated in brake repair and certification operations. These findings point to targeted, low-disruption improvement opportunities such as capacity reallocation, schedule smoothing, and local parallelization of tasks.

From a scientific and engineering perspective, the main contribution of this work is methodological and shows how discrete-event simulation can be applied to aircraft-component MRO logistics to produce actionable performance metrics and to serve as a first step toward an operational digital twin. The model bridges descriptive operational knowledge with quantitative analysis, making it suitable as a template for similar MRO centers that seek to modernize logistics under Industry 4.0 paradigms.

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AN ANALYSIS OF LOGIMAT SYSTEMS FOR EFFICIENT ITEM STORAGE

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Abstract: This paper presents a comprehensive analysis of optimizing a warehouse storage system by integrating automated Vertical Lift Modules (VLMs) of the Logimat type with a traditional two-story shelving system. The primary objective was to identify the optimal configuration of storage equipment and personnel to enhance spatial and operational efficiency. The methodology is based on a series of simulation experiments using real-world data from a peak operational month, covering 6,210 distinct items and 500,000 picking operations. The study evaluates two core item placement strategies based on ABC analysis and compares different staffing models. The results indicate that an optimal configuration consists of 8 Logimat units and 260 shelving racks. This hybrid system, combined with a role-separated staffing model of 11 "runners" and 4 dedicated VLM operators, achieves a 66.8% reduction in floor space while increasing overall productivity and providing the flexibility to manage peak demand effectively.

Keywords: Warehouse Optimization, Logimat, Vertical Lift Module (VLM), ABC Analysis, Simulation.

Introduction

n the competitive landscape of modern logistics, the efficiency of warehouse operations is a critical determinant of a company's success. Traditional warehouses, often reliant on single-level static shelving, face significant challenges related to spatial inefficiency, high labor intensity, and slow order fulfillment cycles. The manual process of picking items involves extensive travel time for workers, which constitutes a major non-value-added activity and a primary operational bottleneck. As businesses grow and product assortments expand, these inefficiencies are magnified, leading to increased operational costs and a decreased ability to respond to market demands.

To address these challenges, companies are increasingly turning to automation. Automated Storage and Retrieval Systems (AS/RS), particularly Vertical Lift Modules (VLMs), offer a compelling solution. VLMs such as the Logimat system utilize vertical space to create high-density storage, drastically reducing the physical footprint required. By delivering items directly to the operator (the "goods-to-person" principle), they minimize worker travel time, reduce physical strain, and can significantly improve picking accuracy and speed.

This paper presents the results of a detailed study aimed at optimizing an existing warehouse that currently relies exclusively on a traditional shelving system. The core of the study is to evaluate the implementation of a hybrid model that combines a new two-story shelving system with a fleet of Logimat VLMs. The primary research objectives were to:

1. Determine the optimal number of Logimat units required to store the full product assortment while balancing investment costs and capacity.
2. Identify the most effective item placement strategy (slotting) based on ABC analysis to maximize picking efficiency.
3. Establish the optimal number of workers and their roles (generalists vs. specialists) to ensure smooth operations during both average and peak periods.

The analysis is grounded in a robust set of real-world operational data and employs simulation modeling to forecast the performance of various configurations.

Literature Review

The optimization of warehouse operations is a well-established field of study, with a significant body of literature dedicated to storage systems, slotting strategies, and workforce management. The transition from traditional to automated systems is a central theme in contemporary logistics research. Richards (2021) provides a broad overview of modern warehouse management, emphasizing that the strategic integration of automation is key to achieving a competitive advantage through enhanced efficiency and scalability.

A cornerstone of efficient warehouse management is the application of slotting strategies, which dictate the placement of items within the storage facility. The ABC analysis, a method of inventory categorization, is a fundamental tool for this purpose. As described by Duque-Jaramillo et al. (2024), this technique classifies items into categories (A, B, C) based on their picking frequency or turnover rate. High-frequency 'A' items are typically placed in the most accessible locations to minimize travel time, while low-frequency 'C' items can be stored in less accessible areas. This study directly applies this principle to decide which items are best suited for the VLM system versus the conventional.

The performance of VLMs and other "goods-to-person" systems has been extensively analyzed. Tavira et al. (2024) utilized simulation-based analysis to compare picking policies in VLM-equipped warehouses, concluding that system performance is highly dependent on factors such as batching strategies and the synchronization of operator tasks. Their work highlights the necessity of detailed simulation, as employed in this study, to accurately predict the real-world performance of a proposed system and avoid unforeseen bottlenecks. The technical specifications and operational parameters of the Logimat system itself are derived from manufacturer documentation, ensuring the simulation model is based on realistic performance metrics (SSI Schaefer, 2021). This research builds upon these established principles by applying them to a specific industrial case, providing a practical roadmap from analysis to implementation.

Methods and Methodology

The study was structured as a multi-phase project involving data analysis, system modeling, and a series of simulation experiments.

Baseline System and Assortment Characterization

The analysis began with a thorough evaluation of the current warehouse state. The existing system consists of a single-level layout with 600 shelving units, offering 12,000 storage positions and occupying a total floor area of 1,250 m². This system is operated by 18 workers per two shifts, who perform all tasks universally.

The core operational data was extracted from a peak month, representing the annual high in picking intensity. The key data points are:

- Total assortment: 6,210 SKUs (Stock Keeping Units).
- Actively picked assortment: 5,285 SKUs (85.1%).
- Total picking operations (picks): 500,000 per month.

An ABC analysis was performed on the actively picked assortment to categorize items based on their picking frequency:

- **Group A:** 1,840 SKUs (34.8% of picked items). These are the highest-frequency, most critical items.

- **Group B:** 1,126 SKUs (21.3% of picked items). These are items with a medium turnover rate.
- **Group C:** 2,319 SKUs (43.9% of picked items). These are the low-frequency, long-tail items.

Proposed System and Experimental Design

The proposed solution consists of a hybrid system featuring a two-story shelving structure and a variable number of Logimat Starter VLMs. The key components have the following specifications:

- **Shelving System:** 260 racks (1282 x 500 mm), organized over two floors connected by a mezzanine, providing approximately 5,200 primary storage positions.
- **Logimat VLM:** Each unit has a footprint of 7.22 m², a height of 10,050 mm, and a maximum payload of 20 tons. It offers an average tray exchange time of 42 seconds, corresponding to a theoretical capacity of 86 exchanges per hour.

Two series of experiments were conducted:

1. **Hardware Configuration Experiments:** The goal was to find the minimum number of Logimats needed to store 100% of the 6,210 SKUs. Two opposing placement strategies were tested:
   - **Strategy 1 (Least-Picked to Logimat):** Low-turnover C-category items were prioritized for the VLMs. The number of Logimats was simulated from 11 down to 7.
   - **Strategy 2 (Most-Picked to Logimat):** High-turnover A and B-category items were prioritized for the VLMs. The number of Logimats was simulated from 17 down to 8.
2. **Staffing and Workflow Experiments:** Based on the optimal hardware configuration, this phase aimed to determine the best staffing model. The current model (18 universal workers) was compared against a reduced traditional model and a specialized model separating roles into "Runners" (for shelves) and "Operators" (for Logimats). Simulations were run using a batch size of 4 orders per picking tour and two different standard pick times (a standard 15 seconds and an optimized 11 seconds) to measure productivity.

Results and Discussion

The simulation experiments provided definitive results that guided the final recommendations for both the physical infrastructure and the operational workflow.

Phase 1: Optimal Hardware Configuration and Placement Strategy

The experiments to determine the required number of Logimats revealed a critical dependency on the chosen placement strategy. The results clearly showed that a different minimum number of VLMs was required for each strategy to avoid leaving items unplaceable.

Under Strategy 2 ("Most-Picked to Logimat"), where high-velocity items were placed in the VLMs, a minimum of **9 Logimat units** were required to house the target items. Reducing the number to 8 units resulted in 71 items (1.14%) being left without a storage location.

Conversely, under Strategy 1 ("Least-Picked to Logimat"), the system was able to accommodate 100% of the 6,210 SKUs with only 8 Logimat units. It was only when the number of VLMs was reduced to 7 that the system's capacity became insufficient, leaving 246 items (3.96%) unplaceable. The critical thresholds for both strategies are summarized in Tab. 1.

Tab. 1 Critical Capacity Thresholds for Placement Strategies

Strategy Logic	**Experiment**	**No. of Logimats**	**Stored Items**	**Unplaceable Items**
Least-Picked to Logimat	4	8	6,210 (100%)	0 (0%)
Least-Picked to Logimat	5	7	5,964 (96.04%)	246 (3.96%)
Most-Picked to Logimat	11	9	6,210 (100%)	0 (0%)
Most-Picked to Logimat	12	8	6,139 (98.86%)	71 (1.14%)

Based on these results, the configuration with 8 Logimats using the "Least-Picked to Logimat" strategy was identified as optimal. This approach is superior for several reasons. It minimizes the capital investment in automation while still achieving the necessary storage density. More importantly, it creates a more efficient operational workflow. The Logimats become a high-density buffer for slow-moving items, accounting for 52.9% of the SKUs but only 5.3% of the total picks. The fast-moving items, which drive 94.7% of the picking activity, remain in the highly accessible shelving system. This decouples the high-velocity picking process from the mechanical cycle time of the VLMs, preventing the automation from becoming a bottleneck.

Phase 2: Optimal Staffing Model

The simulation of different staffing models for the optimal 8-Logimat configuration revealed stark differences in performance, especially under peak-day conditions. The analysis confirmed that a simple reduction of the current universal-worker model is not viable. A reduced team of workers in the traditional model would not be able to process the peak workload within a single shift, leading to significant delays.

The model based on a separation of roles proved to be far more effective. A configuration of 11 "runners" (for shelves) and 4 dedicated "Logimat operators" (for a total of 15 workers, meaning a split of ~6 runners and 2 operators per shift) was able to handle the peak-day workload efficiently within the allotted time. This model introduces several key advantages:

- **Parallelization:** Runners can pick from shelves concurrently while operators prepare batches of items from the Logimats.
- **Specialization:** Dedicated operators become highly proficient with the VLM interface, reducing pick times and errors. Runners can focus on optimizing their routes within the shelving area.
- **Flexibility and Buffer Capacity:** During the busiest periods, the two operators can fully absorb the VLM workload. During quieter times, or after their primary tasks are complete, they can be reassigned to other tasks, such as assisting runners or replenishment, providing a valuable buffer. A comparison of the conceptual models is shown in Tab. 2.

Tab. 2 Conceptual Comparison of Staffing Models for a Peak Day

Model	Staff (per 2 shifts)	Expected Performance	Meets shift deadline?	Flexibility
Traditional	18 Runners	Baseline	Yes	Low
Reduced Traditional	12 Runners	Overloaded	No	Low
Role Separation	11 Runners + 4 Ops	Optimized	Yes	High

The combination of the optimal hardware configuration and staffing model yields substantial, measurable improvements across all key performance indicators when compared to the current state. The implementation of the two-story shelving system and 8 Logimats reduces the required warehouse footprint from 1,250 m² to just 414.6 m², a remarkable spatial saving of 66.8%. This frees up over 835 m² of floor space for future expansion or other value-added activities.
Operationally, the new workflow reduces the average distance traveled per worker and the time spent on non-productive transfers. The average time spent on transfer per worker decreases by 13.3%. This, combined with the optimized placement of items, leads to a significant boost in productivity. The number of picks per runner per hour increases by 5.7%, and the number of orders processed per worker increases by 14.3%. All this is achieved with a smaller workforce of 15 people, a 16.7% reduction from the current 18.

Conclusion

The primary objective of this comprehensive study was to design and validate an optimized warehouse solution that leverages automation to overcome the limitations of a traditional, manual system. The analysis confirms that a hybrid model, intelligently combining conventional shelving with Vertical Lift Modules, offers a transformative path to greater efficiency.
The definitive recommendation is an integrated system composed of 260 two-story shelving units and 8 Logimat VLMs. This configuration successfully accommodates 100% of the 6,210-item assortment. The most effective operational strategy involves a specific slotting policy where low-turnover items are stored in the high-density Logimats, while high-turnover items are placed in the easily accessible shelving. This approach balances storage capacity with picking throughput, ensuring that the mechanical speed of the automation does not hinder the fast-paced picking of popular items.
Furthermore, the study demonstrates that optimizing the physical system must be paired with an evolution in workflow and staffing. The optimal personnel structure is a specialized model of 15 employees (11 "runners" for shelving and 4 dedicated "Logimat operators") working across two shifts. This model not only reduces the total workforce by three but also introduces parallel processing and operational flexibility, enabling the system to effectively absorb peak demand without compromising performance.
In summary, the proposed solution delivers profound benefits: a 66.8% reduction in floor space, a 14.3% increase in orders processed per worker, and the operational robustness to handle future growth. This represents a fundamental shift from an extensive, low-efficiency warehouse to an intensive, high-productivity logistics operation.

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COLLABORATIVE LOGISTICS AS AN INNOVATIVE STRATEGY IN LOGISTICS MANAGEMENT

Marek ONDOV – Martin STRAKA – Peter KAČMÁRY – Kristína KLEINOVÁ

Abstract: The logistics landscape is evolving, focusing on the shift from traditional to collaborative logistics within supply chains. Traditional logistics emphasizes internal control and simplicity, whereas collaborative logistics fosters cooperation among multiple companies to optimize resources, reduce costs, and enhance sustainability. The study defines collaborative logistics in contrast to outsourcing, highlighting its emphasis on shared goals, trust, and joint decision-making supported by advanced technologies such as cloud platforms, blockchain, and real-time data exchange. A model for implementing collaborative logistics is proposed, detailing steps including role definition, pilot projects, trust-building, and equitable benefit-sharing. The paper discusses the benefits of collaboration, including improved asset utilization and environmental impact, alongside challenges like complex coordination and risk management. The findings suggest that collaborative logistics represents a strategic approach to modern supply chains, enabling increased efficiency, resilience, and sustainability through technological integration and cooperative governance.
Keywords: Collaborative Logistics, Traditional Logistics, Outsourcing, Model.

Introduction

Logistics in the 21st century has shifted from managing flows within individual companies to managing flows between companies. Companies create a complex network of logistics processes in the form of supply chains. A supply chain is a network of organizations engaged in both downstream and upstream material flows through various processes and activities that deliver value in the form of products and services according to the requirements of the end customer. Effective supply chain management plays a key role in reducing costs, improving the quality of customer service, and strengthening competitiveness [1].

Modern technologies enable companies within supply chains to better leverage the potential of partnerships and shared logistics processes, thereby optimizing resource utilization, reducing costs, and improving sustainability across the supply chain. Collaborative logistics is an innovative strategy that involves close cooperation among stakeholders in logistics with the aim of optimizing both resources and processes [2].

The collaborative approach relies heavily on a robust technological infrastructure for real-time information exchange and integrated planning, which are crucial for minimizing waste and mitigating environmental impact. Collaborative logistics reorganizes asset ownership, planning, and information in order to pool capacities, reduce unit costs, and lower emissions. However, it places greater demands on coordination, management, and the integration of information technologies [2,3].

This form of cooperation requires flexibility and adaptability. Collaboration enables companies to achieve better results by combining their efforts, resources, and expertise. Moreover, collaboration can help businesses expand into new markets, gain access to new opportunities, and foster innovation and development through knowledge sharing. A shift toward a “we” mentality, rather than a “we versus them” mentality, supports a positive environment and enhances mutual understanding within supply chains [4].

The aim of this paper is to define the position and form of collaborative logistics in relation to traditional logistics and outsourcing. Within the specification of collaborative logistics, the intention is to develop a model of the modern understanding of collaborative logistics across industry sectors.

Literature review

Traditional logistics keeps assets and planning within a single firm or contracted third-party logistics provider (3PL), which simplifies control but limits utilization and aggregation benefits. Collaborative approaches involve competing shippers or carriers pooling deliveries, sharing terminals, and aligning schedules to consolidate flows and create synergies. Partners may also co-invest incrementally in hubs to reduce upfront risks while enabling joint logistics processes. Even fleet sharing is considered a collaborative logistics approach that enhances utilization by optimizing strategic and operational decisions under uncertainty [5,6].

These approaches offer advantages such as mitigation of risks, higher asset utilization, lower unit transportation costs, shared capital burden, and increased flexibility through pooled resources. On the other hand, disadvantages and new risks of collaboration arise. These include requirements for legal and commercial frameworks, trust, profit-allocation mechanisms, and complex negotiations to achieve stable coalitions [5,6].

One significant risk is the potential disruption of collaboration due to factors such as bad weather, natural disasters, or other unforeseen events, which can cause production delays and increased costs [7]. Furthermore, reputation risk poses a challenge as it may discourage participation in collaborative networks despite their environmental and economic benefits. Reputation risk assessment frameworks can support the sustainability of collaborative networks by strengthening relationships among suppliers, logistics service providers, and end customers [3].

Collaborative logistics can both mitigate and introduce risks. It creates interdependencies that may propagate shocks if governance, information sharing, and contingency rules are weak. In contrast, traditional logistics isolates risks within firm boundaries and has clearer control over contingency plans and liabilities. However, it may lack flexible recovery options and fail to respond effectively to large disruptions [8].

Cost outcomes of collaboration depend on design, profit-sharing rules, and operational flexibility. Collaboration requires investment in joint IT systems, contractual design, and change management, which can offset early gains. Robust cost-sharing rules and negotiation protocols are essential to sustain benefits even if the coalition becomes destabilized. After initial investments, economic benefits emerge from reduced operational costs, consolidated logistics processes, or order and cost splitting. Profit allocation models encourage participation and fair distribution of gains in many collaborative frameworks [9].

Collaborations struggle to extend beyond pilot scopes due to consensus and integration challenges, which increase with the absence of digital platforms, common data standards, and fair allocation rules. Successful collaboration depends on compatible IT, analytics, and coordination mechanisms. Although technologies raise implementation complexity, they enable KPIs, scalability, and environmental gains. Traditional operations typically use internal TMS/WMS stacks with lower integration burdens but reduced cross-firm visibility. Efficient implementation of collaboration and information sharing requires technologies such as [6,9]:

- Cloud-based centralized digital hubs where participants share forecasts, capacity availability, and performance metrics,
- Blockchain and smart contracts are fundamental for trust-based data sharing, automated settlement, and secure provenance tracking,
- Sensor-equipped assets provide live location and dynamic control with proactive troubleshooting,
- Predictive demand forecasting, capacity planning, and dynamic pricing models support collaborative decision-making.

Typical KPIs positively influenced by collaboration include total distribution cost, maintenance cost, vehicle kilometers or number of vehicles, wait time or lead time, inventory levels or shelf availability, CO2 emissions, and fuel or energy consumption [9,10].

Traditional logistics also includes the concept of outsourcing, which in many aspects can resemble collaborative logistics. Outsourcing is a business strategy where an organization transfers certain functions, processes, or services to a specialized company. This approach allows organizations to focus on their core competencies and strategic goals while reducing operational costs and risks. The risk and responsibility for task execution are transferred to external service providers, enabling more efficient resource utilization and access to specialized expertise without maintaining these functions in-house [11].

Collaboration is distinguished from outsourcing by its fundamental nature and approach. While outsourcing primarily involves delegating specific functions or tasks to external providers, collaboration emphasizes a shared purpose and joint achievement of goals. The outsourcing relationship is transactional and task-oriented, with specific services delivered by external providers according to pre-established conditions and goals monitored independently. In contrast to outsourcing, which may involve more hierarchical or transactional relationships, collaboration focuses on co-creation and collective decision-making. It requires continuous coordination, cooperation, and adaptation to achieve common objectives [12,13].

Results and Discussion

The literature review in the previous chapter clearly defines the difference between collaborative logistics and outsourcing. The difference lies in the transactional nature of outsourcing, where the supplier of knowledge, services, or processes does not establish other relationships or ties with the ordering party. However, the distinction between traditional logistics and collaborative logistics needs to be clarified and structured.

Traditional logistics vs. Collaborative logistics

The choice between collaborative and traditional logistics models represents a fundamental strategic decision involving trade-offs between efficiency and control. Collaborative logistics offers compelling economic and environmental benefits but requires significant organizational transformation and technology investment. Traditional logistics relies on direct control and operational simplicity and allows for higher decision-making flexibility but has limited IT integration capabilities in competitive environments. Table 1 presents a comparison based on different dimensions.

Tab. 2 Comparison of Traditional and Collaborative logistics

Dimension	Traditional logistics	Collaborative logistics
Cost Efficiency	Baseline	Reduction of costs
Environmental Impact	Higher negative impact	Reduction of negative impact
Asset utilization	Lower	Higher
Complexity	Simpler systems	More complex systems
Risk Management	Centralized risk	Distributed risk
IT	Basic IT systems	Advanced IT integration
Coordination	Simple relationships	Multi-party
Control	Direct	Shared, multiple layers

Collaborative logistics model

Collaborative logistics is a modern approach that enables multiple companies to work together to make their logistics operations more efficient. Based on information obtained from available sources and logistics principles, it is possible to create a model for implementing collaborative logistics into company processes. For the prepared model, the following main implementation tasks of collaborative logistics can be defined:

1. Define roles, data-sharing protocols, and performance KPIs upfront,
2. Pilot on a small scale but scale quickly,
3. Use neutral brokers to build trust and manage operations impartially,
4. Focus on transparency and high-quality sharing relevant to all stakeholders,
5. Ensure equal distribution of cost savings and benefits to motivate continued participation.

According to the defined main tasks and monitored dimensions in collaborative logistics, its implementation model is shown in Fig. 1.

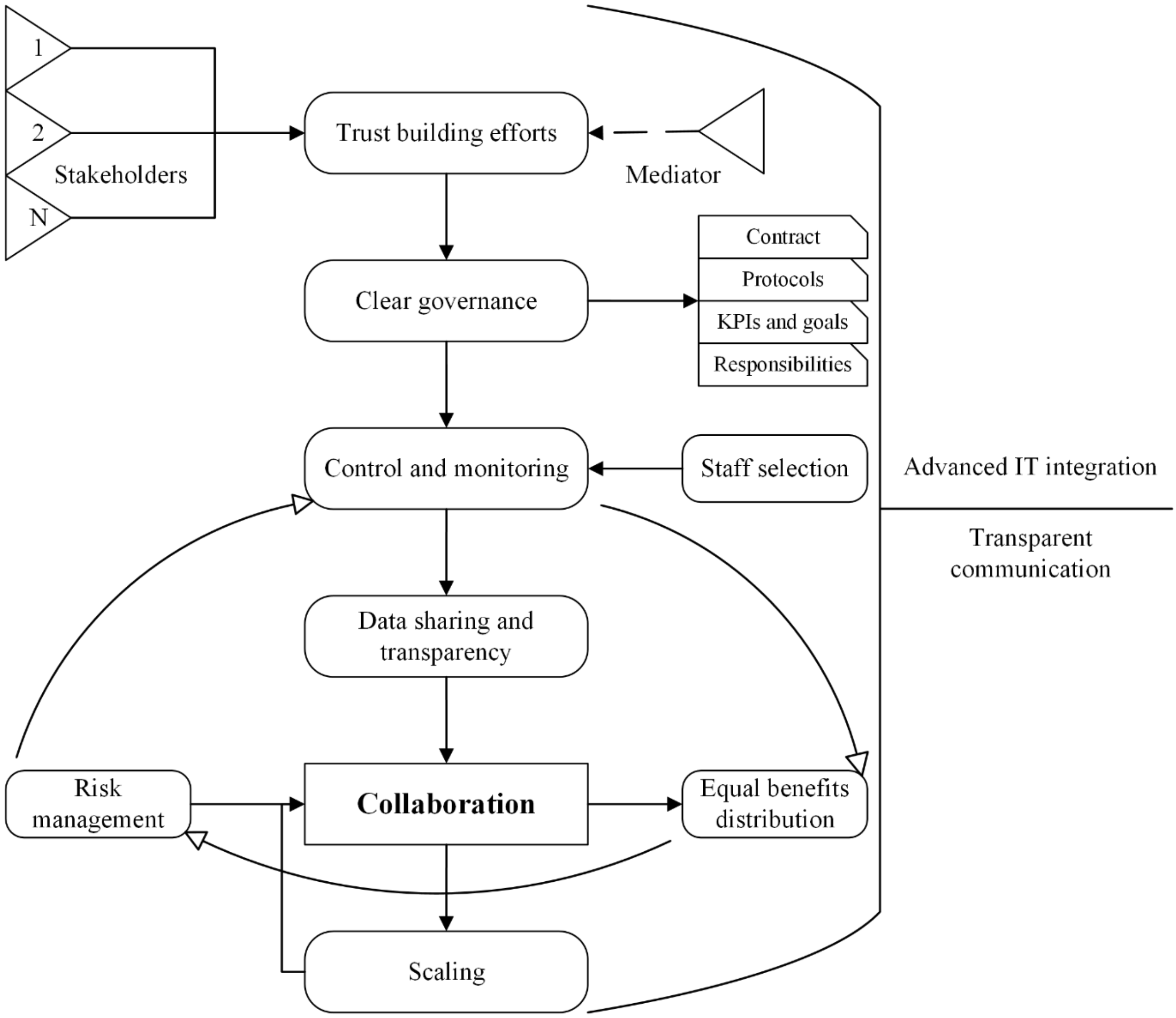

Fig. 1 Collaborative logistics model

The entire model can be divided into two basic parts. The first part involves establishing cooperation, building trust, and preparing the legal framework for collaboration. Subsequently, all stakeholders form a single team responsible for managing, controlling, and monitoring the shared process. The second part is a loop where the main collaboration occurs in the shared process, including joint risk-sharing and fair management of the benefits and savings generated by sharing the process. At the end of the model, scaling activities ensure the development of cooperation towards additional operations or processes. The entire collaborative logistics framework, within the context of Industry 4.0 and 5.0, depends on the integration of advanced technologies and continuous transparent communication. Collaborative logistics represents a paradigm shift from asset ownership to asset sharing, trading operational simplicity for economic and environmental efficiency gains.

Conclusion

In the current environment, where market conditions are influenced by globalization and technological advancement, effective management of logistics processes is considered a key success factor for every company. Companies seek ways to reduce costs while maintaining efficiency and quality. Extended traditional logistics is suitable when full control over the process is required, focusing on simple operations with lower production volumes, or when greater decision-making freedom is needed. Outsourcing, as part of traditional logistics, cannot be confused with collaborative logistics because its nature is purely transactional. Collaborative logistics, based on unity and shared profit, is a suitable solution for companies associated in supply chains.

Collaboration in logistics transforms fragmented supply chains into synchronized networks, unlocking efficiency gains, sustainability improvements, and resilience. By adopting clear governance structures, digital enablers, and pilot-driven implementation, organizations can capture shared value and meet evolving market demands. In this sense, a general model for implementing collaborative logistics for supply chain companies has been developed. Applying the model in practice reduces or eliminates risks associated with traditional logistics but simultaneously introduces new risks related to trust and commitment fulfillment in the shared process.

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HAPTIC TECHNOLOGIES FOR INDUSTRY 4.0/5.0: OPERATIONAL AND MANAGERIAL BENEFITS

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Abstract: The ongoing digital transformation of industry is driven by the integration of physical and virtual systems that reshape production processes, organizational models, and business strategies. Virtual technologies such as virtual reality, augmented reality, and digital twins provide immersive environments and real-time simulations that improve decision-making, streamline workflows, and enhance flexibility. In this context, haptic technologies are emerging as a powerful extension, enabling tactile and kinesthetic interaction with digital objects. Their applications include workforce training, product prototyping and design, remote machine control, and quality assurance, where they create value not only in technical but also in economic and managerial dimensions. The adoption of haptic systems can reduce prototyping costs, increase productivity, improve safety, and strengthen competitiveness, while also requiring significant investment and organizational adaptation. Looking ahead, the integration of haptics with artificial intelligence, digital twins, and Industry 5.0 concepts highlights the dual role of these technologies: pushing the boundaries of technical innovation while contributing to sustainable economic value and human-centered industrial development.

Keywords: Digitalization, Virtual Technologies, Haptic Systems, Industry 5.0, Bussiness Processes

Introduction

The digital transformation of industry has evolved into one of the defining drivers of competitiveness in the twenty-first century. While early industrial revolutions focused on mechanization, electrification, and automation, the current wave is characterized by the integration of digital and physical systems. Digitalization and virtual technologies such as virtual reality (VR), augmented reality (AR), and digital twins represent the backbone of this change, enabling organizations to link physical operations with digital models and simulations. Through these technologies, firms are able to visualize, test, and optimize processes before they are implemented in practice, which not only reduces errors and downtime but also accelerates innovation cycles and increases operational resilience.

This technological shift, however, is not purely a matter of engineering. From a managerial perspective, adopting haptic systems requires evaluating investment costs, workforce training, and organizational adaptation. Firms must weigh upfront expenditures against potential efficiency gains, faster innovation cycles, and enhanced operational resilience. These long-term benefits include cost savings through reduced prototyping and maintenance expenses, higher productivity resulting from optimized workflows, and improved workplace safety achieved through immersive training and remote operations. In this sense, digital and virtual technologies create a direct link between technical progress and economic performance, shaping both the efficiency and the strategic positioning of industrial enterprises in increasingly competitive global markets.

Within this context, haptic technologies have emerged as a particularly promising development. By introducing tactile and kinesthetic feedback into digital environments, haptic systems extend the capabilities of VR, AR, and digital twins beyond visualization and simulation, allowing users to “feel” and manipulate digital objects as if they were real. This makes virtual environments more realistic and useful for industrial applications such as workforce training, prototyping and product design, remote control of machines and robots, and advanced quality assurance. By bridging the gap between digital models and physical experience, haptic technologies deliver not only technical improvements in design and production but also measurable economic benefits through faster development, reduced risks, and greater adaptability.

The growing interplay between digitalization, virtual environments, and haptic interaction highlights the dual nature of industrial transformation. On the one hand, these technologies push the boundaries of what is technically possible, while on the other, they redefine cost structures, efficiency standards, and competitive strategies. Understanding this duality is therefore crucial for both researchers and practitioners seeking to leverage digital tools not only for innovation but also for sustainable economic value creation.

Theoretical Background

Digital and virtual technologies are the foundation of the ongoing transformation in modern industry. Among the most significant are virtual reality (VR), augmented reality (AR), and digital twins. VR creates fully immersive environments that allow users to interact with digital simulations in real time, while AR overlays digital information onto the physical world, thereby enhancing workers’ ability to perform complex tasks with greater precision and efficiency. Digital twins, in turn, provide a virtual replica of physical assets or processes, enabling companies to monitor, simulate, and optimize production systems continuously. Together, these technologies form the basis of cyber-physical systems, where physical and digital environments are tightly interconnected and mutually reinforcing [1].

A particularly dynamic field within this technological landscape is the development of haptic systems. Unlike visual or auditory channels, haptics introduces the sense of touch into virtual interactions. Its functionality rests on two core principles: tactile feedback, which conveys sensations such as vibration or texture, and kinesthetic feedback, which communicates force, weight, or resistance. These mechanisms make digital environments more realistic and intuitive, bridging the gap between abstract simulations and the physical experience of interacting with real-world objects. Devices such as haptic gloves, exoskeletons, and specialized joysticks are designed to capture human motion and deliver appropriate tactile responses. One of the most advanced applications is the data glove, a wearable device that combines motion tracking with tactile actuators to reproduce the feeling of touching and manipulating virtual objects [2].

The integration of haptic systems with VR, AR, and digital twins further enhances their potential. When combined with immersive simulations, haptic technologies allow users not only to visualize but also to physically interact with digital models, which significantly improves training, product design, and operational control. In manufacturing, for instance, operators can practice assembly procedures in a virtual environment while receiving realistic force feedback. Designers can assess the ergonomics and surface quality of digital prototypes before physical production, while remote operators can safely control robots or machinery in hazardous conditions through tactile cues. This seamless connection between simulations and haptic feedback transforms virtual environments into powerful tools for industrial application [3].

Applications of Haptic Technologies in Industry

Haptic technologies are finding a wide range of applications in modern industry, especially when combined with virtual and augmented reality. One of the most promising areas is workforce training. Virtual environments equipped with haptic feedback allow employees to practice assembly procedures, equipment handling, or emergency responses in safe and immersive conditions. This not only improves learning outcomes but also reduces the costs of physical training facilities [4].

Another key application is in prototyping and product design. Haptic interfaces enable designers and engineers to “feel” digital models, assess ergonomics, or evaluate surface properties before a physical prototype is created. This reduces the reliance on costly trial-and-error prototyping and accelerates the innovation process [2].

Haptic technologies are also transforming remote operations. In hazardous or inaccessible environments such as mining, underwater exploration, or nuclear facilities, haptic feedback provides operators with force and resistance cues, allowing them to control machines or robots with much higher precision and safety [5].

Finally, haptic systems can support quality control and workplace safety. They make it possible to detect imperfections during virtual inspections, while training scenarios that simulate high-risk environments improve preparedness without exposing workers to danger. As industries pursue higher standards of efficiency and safety, haptics is increasingly recognized as a valuable enabler of both objectives [3].

Benefits for Business Processes

The integration of haptic technologies into digital industrial systems brings several tangible benefits that span efficiency, costs, safety, and competitiveness. From the perspective of productivity, these solutions enable companies to simulate tasks and workflows before they are carried out in real settings. Employees can train in realistic environments, which shortens learning times, minimizes errors, and allows processes to be optimized without interrupting production.

Another clear advantage lies in cost reduction. Traditional prototyping often requires multiple iterations of physical models, which is both time- and resource-intensive. Virtual prototyping with haptic feedback significantly reduces these expenses by allowing designers and engineers to evaluate ergonomics, material properties, or assembly requirements in a purely digital space. Safety is also improved as workers can rehearse hazardous procedures virtually, gaining valuable experience without exposure to risk. Similarly, remote operations supported by tactile feedback make it possible to control machines or robots in dangerous environments more reliably.

This interconnection between digital and virtual technologies, haptic systems, industrial applications, and business benefits is illustrated in Fig. 1.

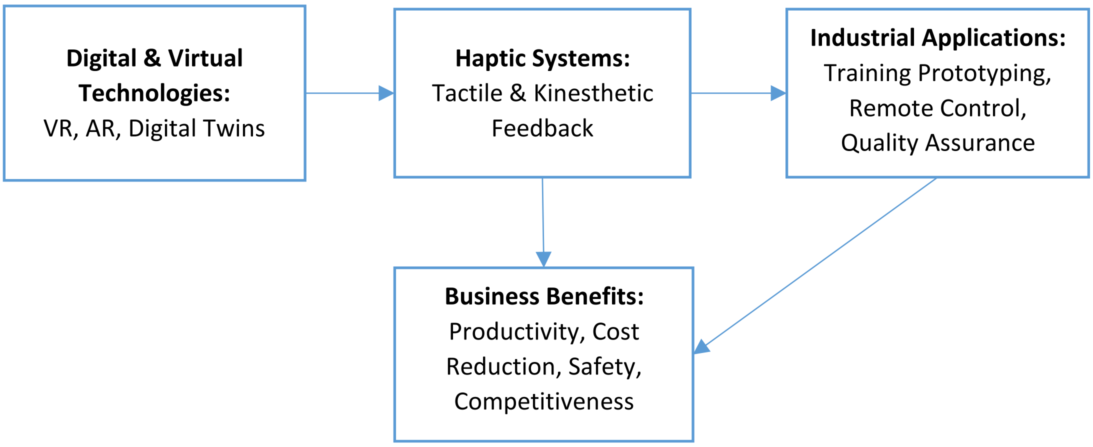

Fig. 1 Interconnection of digital and virtual technologies, haptic systems, and business benefits

Finally, companies that embrace such technologies strengthen their innovative capacity and enhance their market position. Faster product development, more effective collaboration across teams, and the ability to adapt quickly to changing customer demands are all factors that contribute to long-term competitiveness. These outcomes align with the broader industrial transformation associated with Industry 4.0 and the emerging vision of Industry 5.0, which emphasizes the synergy between advanced technologies and human-centered production [1][6].

Economic and Managerial Aspects

The introduction of haptic and virtual technologies into industrial practice inevitably raises questions about costs, return on investment, and managerial implications. Implementation often requires significant upfront investment in hardware, software, infrastructure, and workforce training. From a managerial viewpoint, companies must plan carefully, allocate financial and human resources effectively, and consider potential restructuring of workflows. Successful integration of haptic systems can lead to long-term cost savings, improved employee skill development, and a stronger strategic position in the market. These benefits, including reduced prototyping expenses, increased productivity, and enhanced safety, frequently result in a positive return on investment [8].

From the perspective of product lifecycle management (PLM), haptic-enabled digital environments allow firms to optimize the entire lifecycle of their products. Digital twins enriched with tactile interaction make it possible to anticipate failures, improve design, and refine maintenance processes, thus supporting sustainable and cost-effective operations.

The contribution of haptic technologies to different phases of the product lifecycle is illustrated in Fig. 2. The figure highlights where haptics bring the greatest contribution – design, prototyping, and operation – and emphasizes the central role od haptic systems as a link between digital models and physical experience.

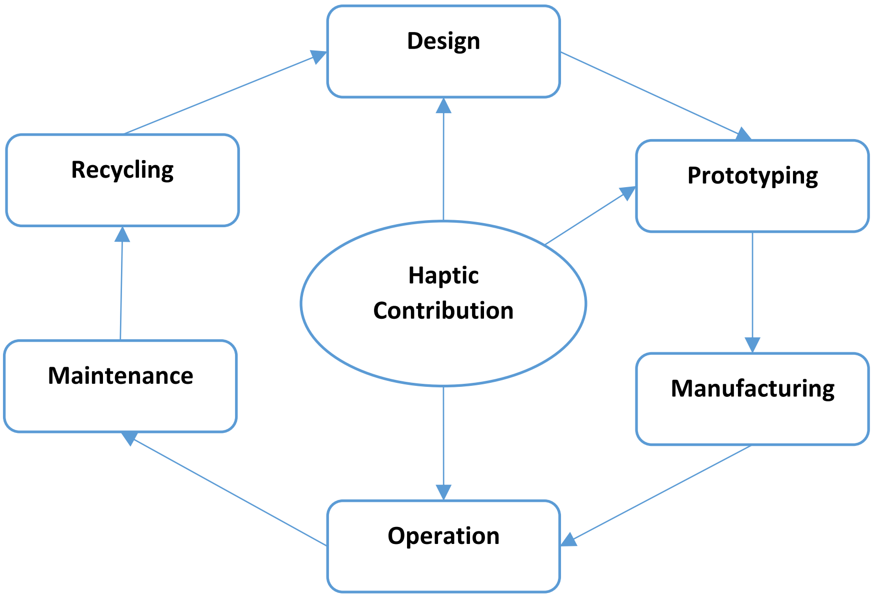

Fig. 2 Product lifecycle and phases influenced by haptic technologies

At the strategic level, the adoption of these technologies enhances firms’ competitiveness and market position. By accelerating innovation cycles, fostering collaboration, and enabling faster adaptation to customer needs, companies gain an advantage in markets increasingly shaped by digital transformation. This trend is especially relevant in the transition from Industry 4.0 to Industry 5.0, where human-centered and personalized production models become key [1][7].

Conclusion

Digitalization and virtual technologies are no longer optional add-ons but essential components of modern industrial systems. By integrating VR, AR, and digital twins, firms have achieved higher efficiency, cost savings, and safer work environments. Within this landscape, haptic technologies provide an additional layer of interaction that transforms virtual experiences into tangible ones. Their ability to combine tactile and kinesthetic feedback opens new opportunities in training, prototyping, remote operations, and quality assurance.

From an economic and managerial perspective, the adoption of haptics requires substantial investments in infrastructure and training, which may pose challenges for smaller firms. Nevertheless, the long-term returns—including reduced prototyping costs, faster innovation, enhanced workforce capabilities, improved workplace safety, and stronger market positioning—demonstrate that haptic technologies are not merely technical novelties but strategic assets for companies navigating Industry 4.0 and 5.0. However, the evidence suggests that long-term benefits such as reduced prototyping costs, increased innovation capacity, and improved workplace safety can outweigh initial expenses. Companies that strategically implement these technologies gain a competitive advantage, particularly as industry shifts toward the principles of Industry 5.0, where human creativity and personalization are emphasized alongside technological advancement.

Looking ahead, several directions emerge. First, there is a need for greater integration of haptic systems with artificial intelligence and digital twins, enabling adaptive, intelligent, and predictive industrial solutions. Second, education and e-learning represent promising fields, where immersive and tactile environments can revolutionize vocational training and engineering education. Third, research should explore not only technical performance but also organizational and cultural factors that influence successful adoption.

For practitioners, the key recommendation is to approach haptic integration strategically: pilot projects in training or prototyping can demonstrate value and justify broader investments. For researchers, there is a growing need to evaluate the long-term economic impact, standardization, and human factors involved in haptic deployment. Ultimately, haptic technologies represent more than just a technical novelty - they are a bridge between the digital and physical dimensions of industry, supporting both economic performance and human well-being.

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IN VITRO CULTIVATION OF CHONDROCYTES IN BIOMEDICAL CARTILAGE ENGINEERING

Jana ČAJKOVÁ– Darina BAČENKOVÁ– Marianna TREBUŇOVÁ

Abstract: Cartilage tissue engineering represents a rapidly developing field that addresses the clinical challenges associated with cartilage defects and degenerative joint diseases. Chondrocytes, the primary resident cells of cartilage, play a fundamental role in maintaining extracellular matrix (ECM) homeostasis. In vitro cultivation of chondrocytes provides a controlled environment for understanding cartilage biology and for generating engineered tissue suitable for implantation. This paper summarizes the principles of in vitro chondrocyte cultivation, highlights current approaches and scaffolding strategies, discusses major limitations such as dedifferentiation, and explores perspectives for biomedical applications.
Keywords: cartilage engineering, chondrocytes, in vitro cultivation

Introduction

Articular cartilage is an avascular, aneural, and alymphatic connective tissue (Fig. 1) with limited intrinsic regeneration capacity [1]. Injuries or degenerative conditions such as osteoarthritis lead to progressive cartilage degradation, often resulting in pain, reduced mobility, and diminished quality of life [2]. Traditional treatment options—including microfracture, autologous osteochondral transplantation, or prosthetic joint replacement—have limitations in terms of donor tissue availability, mechanical integration, and long-term outcomes [3][4]. Tissue engineering offers promising alternatives by combining cells, biomaterials, and signalling molecules to regenerate functional cartilage tissue [4] [5]. Among the cellular candidates, chondrocytes remain the gold standard for cartilage engineering because of their natural ability to produce type II collagen and proteoglycans, which are essential for cartilage function. However, the in vitro cultivation of chondrocytes presents several challenges, primarily linked to their dedifferentiation potential and limited proliferative capacity [6]. This paper provides an overview of methods and strategies for chondrocyte cultivation in vitro, focusing on the requirements for biomedical cartilage engineering.

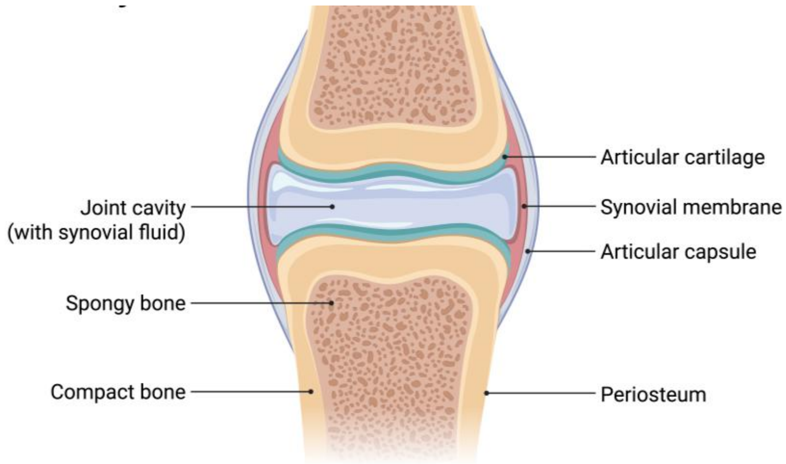

Fig. 1 Synovial Joint Anatomy (created in Biorender.com)

Chondrocyte biology and isolation

Chondrocytes originate from mesenchymal progenitors and reside within lacunae of the extracellular matrix [1]. Their morphology and phenotype are tightly regulated by the three-dimensional (3D) matrix and biomechanical environment. For in vitro applications, chondrocytes are typically isolated from articular cartilage tissue using enzymatic digestion (commonly collagenase type II) [6]. After isolation, cells can be expanded in monolayer culture. However, repeated passaging leads to dedifferentiation, where cells shift from a rounded to a fibroblast-like morphology and reduce expression of type II collagen while increasing type I collagen production [7]. This phenomenon limits their direct use in engineering applications. Strategies to counteract dedifferentiation include the use of 3D culture systems, supplementation with growth factors such as TGF-β, FGF-2, or IGF-1, and co-cultivation with mesenchymal stem cells (MSCs) [8].

In vitro cultivation strategies

The successful application of chondrocytes in cartilage tissue engineering depends strongly on how cells are cultivated in vitro [9]. Culture conditions must replicate key aspects of the native cartilage microenvironment to preserve the chondrocytic phenotype and stimulate extracellular matrix synthesis. Over the past decades, several cultivation strategies have been developed, ranging from simple two-dimensional (2D) systems to more advanced three-dimensional (3D) scaffolds, spheroids, and bioreactor-based platforms [10]. Each method provides distinct advantages and limitations, and often a combination of approaches is required to achieve functional cartilage-like tissue (Fig. 2).

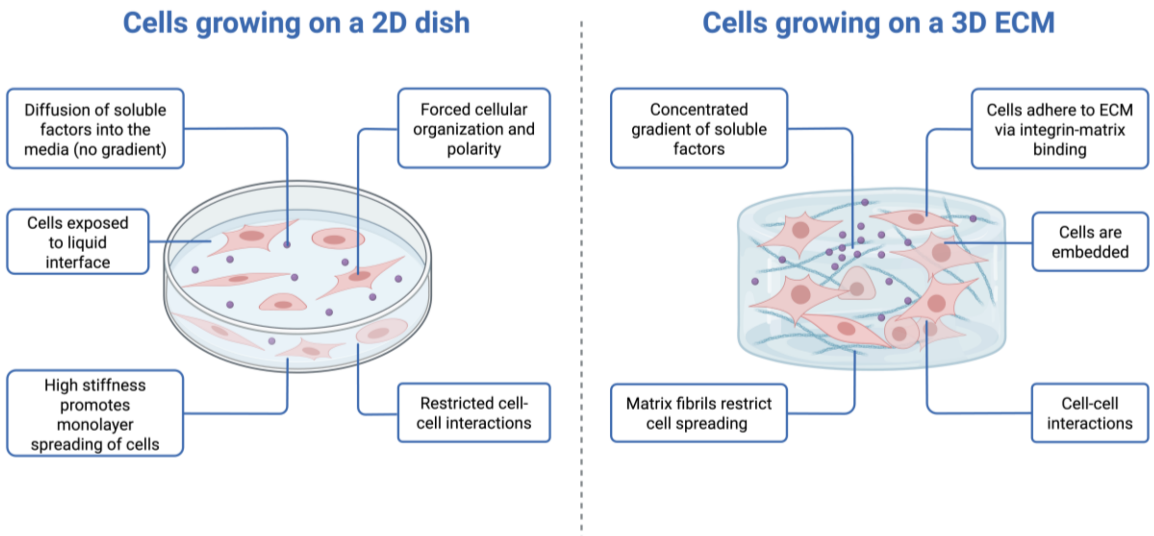

Fig. 2 Comparison of 2D vs. 3D Cell Culture (created in Biorender.com)

Two-dimensional (2D) culture

Monolayer culture, also referred to as two-dimensional (2D) culture, represents the most basic and widely used approach for the expansion of chondrocytes in vitro [11]. After isolation from native cartilage tissue, cells are typically seeded onto tissue culture plastic and maintained in serum-supplemented media. This system is simple, cost-effective, and allows rapid proliferation of chondrocytes, making it particularly useful when a large cell population is required for subsequent applications such as autologous chondrocyte implantation [10]. Despite these advantages, prolonged culture on flat plastic surfaces inevitably leads to phenotypic drift and dedifferentiation. Chondrocytes gradually lose their rounded morphology and adopt a fibroblast-like shape [12]. On the molecular level, this transition is characterized by a decrease in cartilage-specific extracellular matrix production, particularly type II collagen and aggrecan, accompanied by an increase in type I collagen expression, which is typical for fibrocartilage [13]. As a result, the cells no longer mimic the functional phenotype of native articular chondrocytes, limiting their direct utility in cartilage engineering. To mitigate these drawbacks, researchers have explored several modifications to standard 2D culture. Supplementation of culture media with growth factors such as TGF-β, IGF-1, or FGF-2 can help sustain the chondrogenic phenotype during early passages [14]. Similarly, coating culture surfaces with extracellular matrix proteins like collagen type II, fibronectin, or laminin provides additional biochemical cues that partially preserve chondrocyte function. Low oxygen tension (hypoxic culture, 2–5% O_2) has also been shown to maintain matrix production and reduce dedifferentiation [15]. Nevertheless, 2D systems remain inherently limited because they cannot replicate the three-dimensional microenvironment of cartilage tissue. Therefore, while monolayer culture is valuable for cell amplification, it is generally used only as a preparatory stage before transferring chondrocytes into three-dimensional scaffolds or dynamic culture systems that better support their redifferentiation and matrix synthesis [16].

Three-dimensional (3D) scaffolds

Three-dimensional scaffolds provide a microenvironment closer to native cartilage, allowing chondrocytes to maintain their rounded morphology and cartilage-specific phenotype. Natural hydrogels such as alginate, agarose, collagen, or hyaluronic acid offer high biocompatibility and support redifferentiation, while synthetic polymers (PLA, PGA, PCL) contribute tunable mechanical strength and degradation rates [17] [18]. Hybrid systems often combine the biological activity of natural materials with the stability of synthetic ones. Scaffold architecture strongly influences cell behavior: high porosity and interconnected pores ensure nutrient diffusion and ECM deposition [19], whereas stiffness modulates morphology and matrix production. Bioactive modifications—including growth factors (TGF-β, BMPs, IGF-1), adhesive peptides (RGD), or ECM components—further enhance chondrogenic activity. Integration with bioreactors enables dynamic culture under compression, shear, or hydrostatic pressure, improving both ECM synthesis and mechanical functionality of the constructs. Main challenges include ensuring uniform cell distribution, controlling scaffold degradation, and avoiding adverse immune reactions [20]. Brand et al. developed a method for culturing human articular chondrocytes in a 3D system using high concentrations of synovial fluid (up to 100%) for 21 days. They overcame the technical challenge of the fluid’s high viscosity and showed that this approach better mimics the native cartilage environment compared to standard artificial media. Their system provides a platform to study chondrocyte behavior in synovial fluid and supports future applications in cartilage regeneration and arthritis therapy [21].

Scaffold-free approaches

In addition to scaffold-based systems, several strategies have been developed that rely on the intrinsic ability of chondrocytes to form three-dimensional aggregates without the use of exogenous biomaterials [22]. These scaffold-free approaches aim to exploit cell–cell interactions and self-assembly processes that more closely mimic early stages of cartilage development. One of the most established methods is pellet culture, in which isolated chondrocytes are centrifuged into compact aggregates and maintained under chondrogenic conditions [23]. Pellet cultures have been widely used as a model system for studying cartilage biology and testing chondrogenic differentiation protocols [24]. Another promising approach is the formation of spheroids or microtissues, where chondrocytes spontaneously self-assemble into rounded, multicellular aggregates. Spheroid systems provide high cell density and strong intercellular communication, both of which are critical for functional ECM production [25]. In recent years, spheroids have gained popularity as building blocks for modular tissue engineering, where multiple microtissues are fused into larger constructs suitable for implantation [26]. The mechanical strength of spheroids or pellets is initially low, making them difficult to handle and implant in load-bearing sites. Nutrient diffusion can also be restricted in larger aggregates, leading to necrotic centers if culture conditions are not optimized. To address these issues, dynamic culture systems (e.g., perfusion or rotating bioreactors) are often combined with scaffold-free approaches to enhance oxygen and nutrient supply [20] [27]. Lehmann et al. developed a novel scaffold-free 3D culture system to enhance chondrogenesis of human articular chondrocytes from elderly patients. Using spheroids and fused microtissues cultured with TGF-β2 and/or L-ascorbic acid, they generated cartilage-like constructs resembling native hyaline cartilage, with strong collagen II and proteoglycan expression. This approach supports in vitro studies of cartilage regeneration and may contribute to new therapies for cartilage defects and osteoarthritis [28].

Conclusion

In vitro cultivation of chondrocytes forms the foundation of modern cartilage tissue engineering. While 2D culture remains valuable for cell expansion, three-dimensional systems—whether scaffold-based, scaffold-free, or combined with bioreactors—are essential for maintaining the chondrogenic phenotype and generating functional extracellular matrix [7] [22]. Despite challenges such as dedifferentiation, limited mechanical strength, and integration with host tissue, continuous advances in biomaterials, bioreactor design, and cell–matrix interaction studies are steadily overcoming these barriers. Biomedical applications already range from autologous chondrocyte implantation to in vitro disease modeling and regenerative implants, underlining the translational potential of this research. Future progress in bioprinting, gene editing, and personalized scaffold design will likely expand clinical options and improve long-term outcomes for patients with cartilage defects [14]. By combining biological insight with engineering innovation, in vitro cultivation of chondrocytes continues to move closer to delivering reliable, patient-specific solutions in regenerative medicine.

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ADVANCED REPAIR OF CARTILAGE DEFECTS USING BIOENGINEERING

Darina BAČENKOVÁ — Jana ČAJKOVÁ— Marianna TREBUŇOVÁ

Abstract: Cartilage injuries represent a major clinical challenge due to the avascular and aneural nature of cartilage, which severely limits its regenerative capacity. Traditional treatments, such as microfracture, autologous chondrocyte implantation, and osteochondral grafting, provide partial solutions but often fail to restore long-term functionality. Recent advances in bioengineering offer promising alternatives, particularly through the application of biomaterials, tissue engineering, gene therapy, and cell-based therapies. This review summarizes current strategies and highlights novel bioengineering approaches to cartilage regeneration.
Keywords: cartilage repair, bioengineering

Introduction

Articular cartilage covers the ends of long bones and provides a low-friction surface essential for load-bearing and joint mobility. Its unique extracellular matrix (ECM), rich in collagen type II and proteoglycans, provides compressive resistance and resilience [1]. However, the avascular, aneural, and alymphatic nature of cartilage severely limits its intrinsic capacity for self-repair [2] [3]. Even small focal defects frequently progress into larger degenerative lesions, eventually leading to osteoarthritis — a major global health burden. Epidemiological studies estimate that millions of patients worldwide suffer from cartilage-related pathologies (Fig. 1), with rising prevalence due to aging populations and sports-related injuries. The socioeconomic impact includes loss of mobility, chronic pain, decreased productivity, and high healthcare costs. Conventional repair techniques, while clinically established, rarely achieve durable regeneration of hyaline cartilage [4]. This limitation has spurred an increasing interest in bioengineering-based strategies, which integrate biological understanding with material science and biomedical technology. These approaches aim not only to restore tissue continuity but also to reproduce the structural and functional complexity of native cartilage [5].

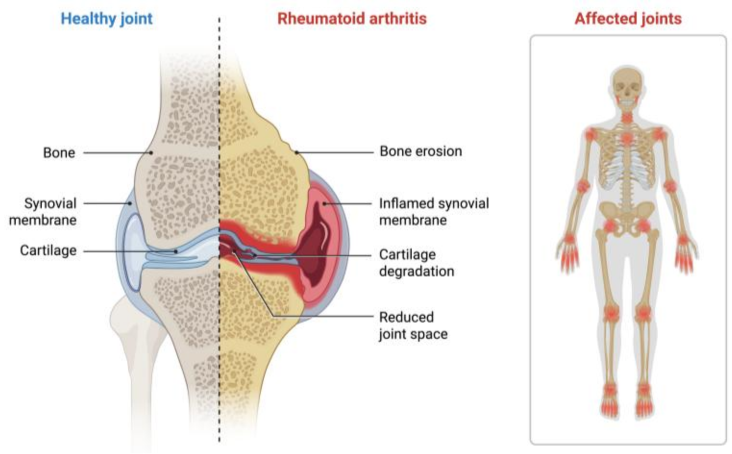

Fig. 1 Inflammation in Rheumatoid Arthritis (created in Biorender.com)

Biological Basis of Cartilage Repair

Native articular cartilage is composed of chondrocytes embedded within ECM rich in type II collagen, proteoglycans, and water [3]. The tissue is organized into superficial, middle, deep, and calcified zones, each with distinct cellular morphology and mechanical properties. Chondrocytes, which account for less than 5% of tissue volume, are terminally differentiated and exhibit low mitotic activity [6]. Consequently, trauma or degeneration rarely triggers sufficient intrinsic regeneration. Bioengineering approaches seek to overcome this limitation by providing exogenous cells, scaffolds, and bioactive signals that recapitulate the hierarchical architecture and biochemical milieu of native cartilage [7].

Scaffold-Based Strategies

A cornerstone of cartilage bioengineering is the design of biomaterial scaffolds capable of mimicking the extracellular matrix microenvironment and providing both structural and biochemical support for tissue regeneration (Fig. 2) [8]. The ECM of native articular cartilage is characterized by a dense network of type II collagen fibers interspersed with proteoglycans such as aggrecan, which together confer high compressive strength, tensile resilience, and hydration capacity [9]. To approximate these properties, scaffolds must not only support cell adhesion and viability but also guide cellular organization, ECM secretion, and long-term integration with host tissue [10]. Authors Yang et al. created a three-dimensional acellular cartilage matrix (ACM) scaffold from bovine cartilage using sequential decellularization, freeze-drying, and UV cross-linking. The scaffold retained collagen and glycosaminoglycans, displayed a porous sponge-like structure, and showed good biocompatibility with rabbit mesenchymal stem cells. In vivo, MSC–ACM constructs significantly improved cartilage repair in rabbit knee defects at 6 and 12 weeks, highlighting ACM as a promising scaffold for cartilage tissue engineering [11].

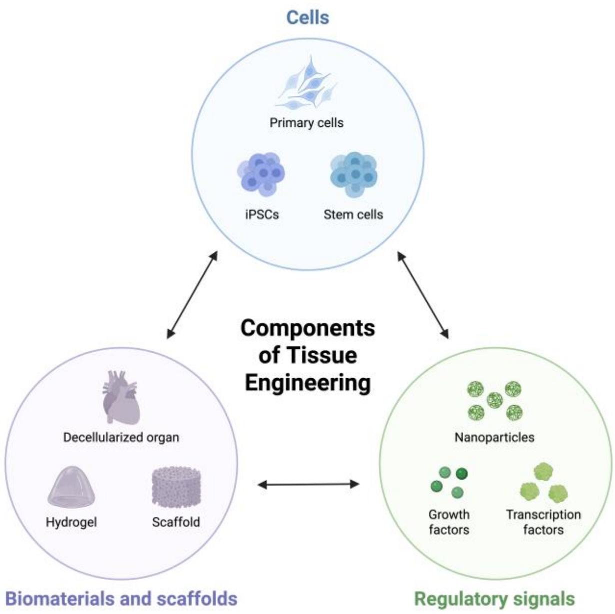

Fig. 2 Summarised components used in tissue engineering process (created in Biorender.com)

Natural polymers

Natural polymers such as collagen, hyaluronic acid, alginate, fibrin, and chitosan are among the most widely investigated materials because they inherently contain bioactive motifs recognized by integrins and other cell receptors [12]. Collagen scaffolds, for instance, provide binding sites for chondrocytes and mesenchymal stem cells (MSCs), facilitating chondrogenic differentiation and matrix deposition [13]. The study of Dorotka et al, tested a type I/II/III collagen matrix with ovine chondrocytes and bone marrow stromal cells in vitro and for chondral defect repair in sheep. Chondrocyte-seeded matrices with microfracture produced the most repair tissue and hyaline-like cartilage, while unseeded matrices offered no added benefit over microfracture alone [14].

Hyaluronic acid contributes to hydration and viscoelasticity, while alginate and chitosan form hydrogels that encapsulate cells in a protective microenvironment [13]. Fibrin gels, derived from blood plasma, are particularly attractive for clinical translation due to their autologous origin and ability to promote rapid cell infiltration [15]. Despite these advantages, purely natural scaffolds often lack sufficient mechanical strength to withstand joint loading, and their degradation kinetics may be difficult to control, leading to premature collapse or prolonged persistence that interferes with tissue remodelling [16].

Synthetic polymers,

The degradation rate, crystallinity, and mechanical stiffness of synthetic polymers can be finely tuned by adjusting polymer composition, molecular weight, and processing conditions [17]. For example, PCL exhibits a slow degradation rate and high mechanical stability, making it suitable for load-bearing applications, while PLGA degrades more rapidly, releasing acidic byproducts that must be carefully managed to avoid local inflammation [18]. However, synthetic polymers are biologically inert, lacking intrinsic recognition sites for cell attachment. Consequently, they are often modified with peptides such as Arg-Gly-Asp (RGD) motifs, coated with ECM proteins, or blended with natural polymers to improve cell–material interactions and promote chondrogenesis [19]. The authors Nagura et al. developed a porous poly(DL-lactide-co-glycolide) (PLG) scaffold and tested it in rabbit femoral trochlear osteochondral defects. The scaffold supported fibrous tissue organization that later regenerated into cartilage at the surface, while new bone formed in the subchondral region as the scaffold degraded. Treated defects achieved significantly higher histological scores compared to controls, indicating that the PLG scaffold effectively promoted osteochondral repair without added cells or growth factors [20].

Advanced fabrication techniques

Special fabrication techniques such as electrospinning, freeze-drying, and especially 3D bioprinting have revolutionized scaffold design [21]. Bioprinting allows precise spatial deposition of biomaterials and cells, enabling the creation of architectures with controlled pore size, interconnectivity, and anisotropy [22]. This capability is particularly valuable for reproducing the zonal heterogeneity of cartilage, where superficial zones require high tensile resistance, while deeper zones must withstand compressive forces. By integrating computer-aided design (CAD) models based on patient imaging, patient-specific scaffolds can be generated to fit irregular defect geometries, improving clinical applicability. Study of Li et al. combined 3D scanning with 3D bioprinting to repair bone and cartilage defects. Defect models of long bones, femoral condyles, and grade IV chondral lesions were digitally reconstructed and printed in situ using photopolymerized hydrogel bioinks. This approach successfully restored defect geometry, suggesting 3D scanning–assisted bioprinting as a promising strategy for regenerative medicine [23].

Smart and stimuli-responsive scaffolds

Scaffold that are able to respond to external stimuli represent a further evolution in this field. These materials are designed to dynamically interact with their microenvironment, releasing bioactive molecules in response to enzymatic activity, pH changes, or mechanical loading [24]. Hydrogels incorporating nanoparticles or microparticles loaded with growth factors such as TGF-β or BMPs enable sustained and localized release, reducing systemic side effects. Mechanically responsive scaffolds that stiffen under compression can provide temporary reinforcement during joint loading while maintaining elasticity at rest [25][26]. Conductive polymers and magnetically responsive nanoparticles are also being explored to deliver external stimulation, such as pulsed electromagnetic fields, which have been shown to enhance chondrogenesis [27].

Tab. 3 Scaffold Strategies in Cartilage Bioengineering [28] [13] [29] [30]

Type	Examples	Pros	Cons
Natural	Collagen, HA, alginate, fibrin	Biocompatible, bioactive, support chondrogenesis	Weak mechanics, fast/variable degradation
Synthetic	PLA, PGA, PLGA, PCL	Tunable strength, reproducible, stable	Bio-inert, acidic byproducts, needs modification
3D Bioprinted	GelMA, alginate bioinks + polymers	Patient-specific, zonal design	Technical, scalability limits
Smart	Nanoparticle hydrogels, conductive polymers	Controlled release, mechano-responsive	Experimental, regulatory hurdles

Conclusion

Bioengineering has significantly advanced the field of cartilage repair by combining scaffold technologies, stem cell biology, and molecular modulation into integrated therapeutic platforms [32]. Although challenges remain in achieving fully functional and durable hyaline cartilage regeneration, ongoing progress in materials science, stem cell technology, and translational research offers realistic prospects for improved clinical outcomes. Advanced bioengineering approaches represent not only a bridge between basic science and clinical practice but also a shift in the management of cartilage defects, moving from symptomatic relief toward true tissue regeneration.

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AUTOMATIC INDEXING OF TECHNICAL DOCUMENTATION USING ARTIFICIAL INTELLIGENCE

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Abstract: The paper focuses on the use of Artificial Intelligence (AI) for automatic indexing of technical documentation. With the growing volume of industrial and engineering data, traditional keyword-based indexing methods become insufficient due to limited scalability and lack of semantic understanding. This study explores modern Natural Language Processing (NLP) techniques, particularly embedding models such as Sentence-BERT and GPT, for semantic indexing and document retrieval. The proposed approach was experimentally evaluated on a set of technical documents, showing improved accuracy in capturing conceptual similarity compared to conventional methods. The results indicate that AI-driven models can significantly enhance the efficiency of information retrieval in industrial documentation systems and highlight the potential for further research on domain-specific model fine-tuning.
Keywords: artificial intelligence, NLP, indexing, embeddings, documentation

Introduction

Technical documentation forms the backbone of any industrial manufacturing and development process. The growing volume of data, specifications, drawings, and protocols necessitates an efficient system for the rapid and precise retrieval of relevant information. Traditional indexing approaches, based on manual keyword assignment or controlled vocabularies, face challenges related to scalability, consistency, and cost-effectiveness.

The concurrent development of Artificial Intelligence (AI) and Natural Language Processing (NLP) offers new opportunities for automated text processing and semantic understanding. Pre-trained language models, such as BERT, Sentence-BERT, or GPT, can comprehend the meaning of words and sentences in context. This capability overcomes the limitations of traditional indexing methods by representing text as numerical vectors (embeddings), which capture semantic relationships between documents.

The primary goal of this work is to explore the application of modern language models for automated indexing of technical documentation within the mechanical engineering industry. This research integrates a theoretical overview, methodological design, experimental validation, and a discussion of practical application potential in industrial systems (e.g., PLM and documentation platforms).

Classical Indexing Approaches

Document indexing is essential for effective Information Retrieval (IR). Classical approaches include manual, keyword-based, and ontology-based (semantic) indexing.

Manual indexing offers high precision but is time-consuming, costly, and difficult to scale for extensive collections [1], making it highly impractical in a big data environment.

Keyword-based indexing uses fast and scalable classical models (e.g., Boolean, vector space) [1]. However, it operates only at the lexical level [1], leading to the vocabulary gap where relevant documents are overlooked [4]. The lack of semantic understanding causes ambiguity and leads to irrelevant results [3], ultimately lowering search accuracy [4].

Ontology-based indexing uses structured domain knowledge to map content to concepts, enabling semantic search and disambiguation [3, 4]. This conceptual mapping overcomes synonymy and polysemy [4, 3]. Modern methods enhance scalability by integrating Machine

Learning and NLP [2, 3]. Its primary limitation is the requirement for well-developed domain ontologies, making implementation complex [4].

Advances in Natural Language Processing

Modern Natural Language Processing (NLP) is fundamentally linked to deep learning and the rise of Pre-trained Language Models (PLMs).

The foundation of contemporary NLP is deep learning architectures, notably Transformers, which capture complex linguistic patterns and have effectively replaced traditional linear models [5].

The dominant trend is PLMs (BERT, GPT, T5). The "pre-training and fine-tuning" paradigm enables efficient transfer learning and sets new performance standards [6]. Latest methods utilize prompt-based approaches, facilitating few-shot and zero-shot learning [6].

Supporting techniques include transfer learning to improve performance when labeled data is limited [7], and data augmentation in low-resource scenarios [7]. Future research also explores Quantum Machine Learning to accelerate NLP tasks [8].

Transformer Models in Natural Language Processing

Progress in NLP is centered on the Transformer architecture, specifically BERT, Sentence-BERT (SBERT), and GPT embeddings.

BERT provides deep, contextualized word representations. However, its original embeddings can suffer from anisotropy, limiting performance in semantic similarity tasks [9]. Post-processing techniques are often necessary to address these limitations [9].

SBERT modifies BERT using siamese or triplet networks to produce efficient and semantically meaningful sentence embeddings [10]. SBERT allows fast comparison using cosine similarity, making it highly effective for large-scale semantic search and clustering by significantly reducing computational overhead [10].

GPT-based models use unidirectional pre-training, confirming their strength in generative tasks. GPT embeddings are increasingly used for downstream applications [11]. Extensions like LaBSE [12] broaden applicability to multilingual and domain-specific tasks.

While BERT requires careful post-processing [9], SBERT offers effective sentence embeddings [10]. Current research focuses on contrastive learning to enhance embedding quality [9].

Industrial Deployment of AI-Driven Indexing and Documentation Systems

Artificial Intelligence (AI)-driven systems are transforming industrial environments, particularly in Product Lifecycle Management (PLM).

Bosch exemplifies neuro-symbolic AI, utilizing ontologies and knowledge graphs for semantic data integration [13]. This enables efficient indexing, supports advanced search, and aids applications like digital twins and process optimization [13].

PLM environments are transitioning into intelligent platforms. NLP and Machine Learning automate core processes (documentation, requirements tracking) [14]. AI-driven PLM has shown to accelerate development cycles and improve quality control [14], though integration complexity and data quality remain significant hurdles [14].

AI also extends to Enterprise Information Systems (EIS), transforming information management in manufacturing [15]. Automated documentation reduces manual effort, improves quality, and supports regulatory compliance [16].

Methods and methodology

The proposed solution aims to establish a framework for the automatic indexing of technical documentation using Natural Language Processing (NLP) methods and embedding models. This approach facilitates semantic search and overcomes the limitations of classical keyword-based indexing.

The proposed system comprises five main modules:

1. Data Collection and Preparation: Technical documentation is acquired from internal sources in various formats (PDF, DOCX, text manuals). Documents are subsequently converted to plain text, utilizing OCR technology for scanned content.
2. Text Pre-processing: Texts are cleansed of noise (numbers, symbols, units, specific formats). This is followed by tokenization, stop word removal, and lemmatization, ensuring data consistency and redundancy reduction.
3. Generation of Semantic Representations: Vector representations (embeddings) are created for each document or section using a Sentence-BERT model (Reimers and Gurevych, 2019) or, alternatively, GPT embeddings. These representations capture the semantic similarity between texts, allowing for semantic comparison.
4. Vector Indexing and Storage: The generated vectors are stored in a vector database (e.g., FAISS, Pinecone, or Elasticsearch with a vector extension). Each document is represented by its vector and associated metadata (title, source, date, document type).
5. Retrieval and Evaluation: Upon a user query, the query is converted into an embedding and compared against indexed vectors using cosine similarity. Results are ranked by semantic relevance, enabling the retrieval of relevant documents even if they do not contain exact query keywords.

For experimental validation, the system was implemented in a Python environment using the Hugging Face Transformers, FAISS, and LangChain libraries.

The methodology tested three embedding model variants:

- TF-IDF (serving as a baseline for classical indexing),
- Sentence-BERT (all-MiniLM-L6-v2) as a semantic model representative,
- OpenAI text-embedding-3-small as a generative model representative.

Standard metrics for information retrieval were used for evaluation: Precision@k, Recall@k, and mAP (mean Average Precision). The comparison was conducted on a set of test queries simulating real-world user questions (e.g., "M12 bolt tightening torque," "hydraulic drive connection").

Results and Discussion

A sample corpus of 250 technical documents (including assembly manuals, drawing descriptions, and service protocols) in both Slovak and English was compiled for the experiment. The average document length was 2,000 words. Following the methodology, embeddings were generated with a dimension of 384 (SBERT) and 1,536 (GPT embeddings). The FAISS vector database was configured with L2 normalization and $k=5$ nearest neighbors.

The comparison was conducted across three approaches: 1) TF-IDF + Boolean Search (baseline), 2) Sentence-BERT (SBERT) embeddings + Cosine Similarity, and 3) GPT embeddings + Cosine Similarity.

The average results across 20 test queries are summarized below, using standard Information Retrieval metrics:

Tab. 1 Overview of Experimental Results for AI-based Technical Document Indexing

Model	Precision@5	Recall@5	mAP (mean Average Precision)
TF-IDF	0.62	0.48	0.55
SBERT	0.83	0.79	0.81
GPT embeddings	0.85	0.82	0.83

The results indicate that the semantic models (SBERT and GPT embeddings) significantly outperformed the traditional keyword-based indexing. GPT embeddings achieved slightly better scores, particularly with multi-word and synonymous queries, although the difference was not statistically significant given the limited sample size. The system also demonstrated robust performance with multilingual queries, largely attributed to SBERT's multilingual pre-training.

The findings confirm that implementing embedding models enables more efficient and accurate technical documentation indexing compared to classical approaches. Vector representations successfully capture the meaning and context of terms, thereby overcoming the vocabulary gap typical of TF-IDF and Boolean retrieval.

From a practical perspective, the system has the potential to significantly reduce search time in large documentation repositories. In industrial environments, such as PLM systems or digital maintenance archives, this approach could support faster decision-making, worker training, and automated knowledge generation.

However, certain limitations were identified:

1. The necessity for high-quality text pre-processing, especially for documents with highly specialized technical terminology.
2. The lack of well-annotated data for specialized domains, complicating model fine-tuning.
3. High computational resource requirements for larger corpora and high-dimensional embeddings.

Future research should focus on:

- Integrating domain-specific models trained directly on technical documentation.
- Multimodal approaches combining text with images or CAD data.
- Hybrid systems that merge symbolic (ontology-based) and neural approaches for enhanced precision.

Overall, the proposed AI-driven approach demonstrated that it can substantially improve technical documentation indexing, even with a relatively small corpus and simple implementation. This confirms its prospects for mechanical engineering practice and further intelligent knowledge management research.

Conclusion

This work focused on the problem of automated indexing of technical documentation using Artificial Intelligence (AI). Based on a review of existing approaches, it was demonstrated that traditional keyword-based methods fail to effectively capture semantic relationships in specialized technical terminology. Modern approaches, leveraging deep learning and

embedding models such as Sentence-BERT and GPT, bring significant improvements in semantic similarity and the retrieval of relevant documents.
Experimental results indicated that AI models are capable of more precisely identifying the thematic relationship between documents, even when different terminology is used. The findings confirm the potential for implementing such systems in industrial environments, where they can support more efficient knowledge management, reduce manual effort, and improve documentation quality.
Future research directions appear promising in several areas: the expansion of the dataset with multimodal data (e.g., drawing images, CAD files), the integration of domain-specific embeddings trained on technical texts, and the adaptation of few-shot learning methods for cases with limited labeled data. The results of this work can serve as a foundation for designing intelligent indexing systems deployed in industrial settings.

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FDM PRINTING AND ELIMINATION OF THE NEGATIVE EFFECT OF MOISTURE ON FILAMENT

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Abstract: The study deals with the problem of moisture absorption of filaments in FDM 3D printing and its negative impact on print quality and mechanical properties of final products. The main objective is to analyze the behavior of moisture-sensitive thermoplastic filaments such as PLA, PETG, and ABS and to propose a practical solution based on the use of silica gel as a regenerative desiccant. The methods include a literature review, experimental modeling of a filament dryer in SolidWorks, and its integration with a Prusa XL 3D printer. The results confirmed that moisture significantly reduces layer adhesion, surface homogeneity, and optical clarity. The proposed silica gel dryer ensures continuous protection of filaments, enabling stable extrusion and higher print quality. The solution is a cheap and sustainable alternative to commercial filament dryers, offering regeneration and reusability of the desiccant. The findings can be used in both professional and hobby 3D printing applications.
Keywords: *FDM 3D printing, filament, moisture, silica gel, dryer*

Introduction

FDM (Fused Deposition Modeling) is an additive manufacturing process in which a continuous thermoplastic filament is melted in a nozzle and applied layer by layer to the printing surface. The basis for the correct application of the filament to the desired shape is a digital 3D model uploaded in. .gcode format [1]. The printing process is ensured by the movement of the nozzle in the XY planes; after the layer is completed, the height in the Z axis changes and the cycle repeats. The principle of 3D printing is shown in Fig. 1.
The basic terminology and classification are based on ISO/ASTM 52900 (additive manufacturing terminology) [2].

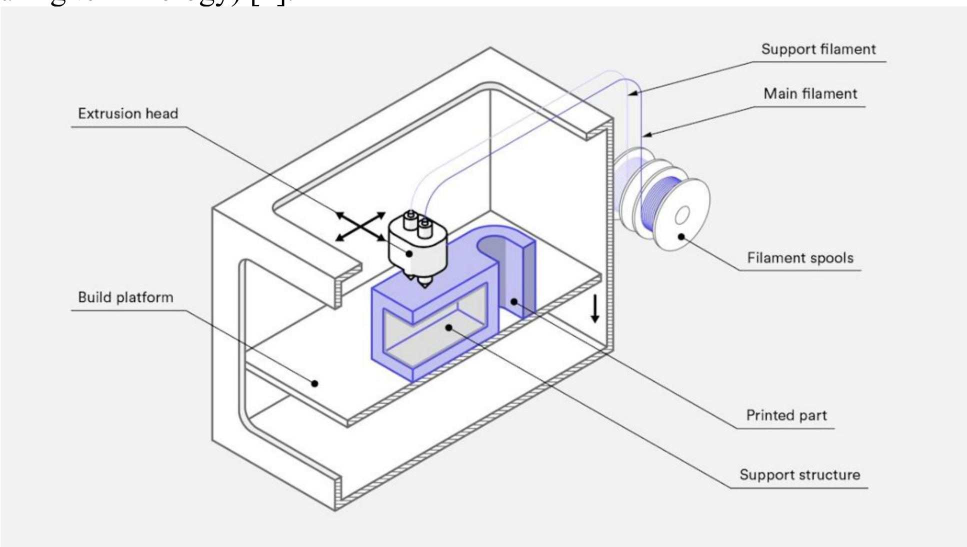

Fig. 1 The principle of 3D printing using the FDM method [4]

Additive manufacturing (AM) is a general term for technologies that gradually build up material to create physical objects according to the specifications of 3D model data. These technologies are currently used for various purposes in the engineering industry, as well as in other areas of

society, such as medicine, education, architecture, cartography, toy manufacturing, and the entertainment industry [1].
Thermoplastic materials are used in FDM 3D printing. The most used materials are PLA, PET-G, and ABS [3].
The first of these, PLA (polylactic acid) filament, is a biodegradable polyester made from renewable sources (corn, sugar cane). It is easy to print, has a low processing temperature and good rigidity, but is more brittle and less heat resistant [5,6]. PLA is slightly hygroscopic, absorbing moisture from the air, especially during prolonged storage without special packaging [7].
PETG (polyethylene terephthalate glycol-modified) is a modified PET with good toughness, chemical resistance, and less brittleness than PLA. It has higher strength but is more susceptible to moisture absorption and often forms strings during printing. PETG is more susceptible to moisture absorption than PLA and absorbs water relatively quickly. Similar to PLA, hydrolytic degradation of ester bonds occurs; the material becomes less viscous and loses its clarity.
Practical consequences:

- bubbles and stringing,
- weaker layer adhesion and higher porosity,
- reduced toughness and chemical resistance,
- in optically clear applications (bottles, covers), moisture will cause cloudiness.

ABS (acrylonitrile butadiene styrene) is an engineering plastic known from industry. It is strong, tough, and more heat-resistant than PLA, but it warps during printing, emits an odor, and requires a heated bed or chamber [5,6]. ABS is less hygroscopic than PLA or PETG, but it can still absorb moisture. Water binds to ABS mainly physically (in amorphous areas), and hydrolytic decomposition is less pronounced than in polyester filaments (PLA, PETG).
Practical consequences of increased moisture in ABS filament:

- moist ABS foams during extrusion and creates pores,
- the surface is bumpy and less homogeneous,
- mechanical properties (especially impact strength) decrease,
- aesthetics and dimensional accuracy deteriorate [8].

Literature review

Additive manufacturing, especially FDM, is being intensively researched for its efficiency, versatility, and wide range of materials [1,3]. Several authors emphasize the sensitivity of PLA, PETG, and ABS to moisture and its negative effects on processing and mechanical properties [5,6]. The hydrolytic degradation of ester bonds in PLA and PETG is a well-documented phenomenon that leads to a reduction in viscosity and clarity [7]. Although ABS is less hygroscopic, it also exhibits deterioration in properties at increased humidity [5]. Existing solutions mainly include heated filament dryers and sealed storage containers, which, however, increase costs and require additional energy. Newer approaches focus on sustainable methods, such as the use of desiccants, with silica gel proving to be very effective due to its adsorption capacity and regenerative properties [8]. This supports the potential for the development of inexpensive, reusable drying systems to increase the reliability of FDM printing processes.

Solutions for reducing the negative impact of moisture on filament

Theoretical knowledge suggests that moisture has a negative impact on print quality and the print itself if filaments are stored incorrectly. Therefore, filaments must be stored in special packaging after opening. When printing from open filaments, it is necessary to remove

moisture. The most ideal device for removing moisture is a dryer with adjustable temperature or a printer function where a drying program can be selected.
An alternative is to make a dryer using silica gel. Silica gel, which is amorphous silicon dioxide, acts as a desiccant. Silica gel was chosen because it can strongly absorb moisture from the environment, up to 40% of its own weight. Another advantage is its ability to regenerate; it only needs to be heated to 100 to 150°C to reactivate its drying capacity.
The solution will be implemented on a Prusa printer, specifically the Prusa XL model with a top cover, which is shown in Figure 2.

Fig.2 Prusa XL

The Original Prusa XL is one of the most innovative 3D printers on the market. Thanks to its state-of-the-art tool changer, which can handle up to five print heads, top-notch print quality, extreme precision, huge print volume, and the ability to print without waste [8].
The Prusa XL printer has 5 print heads with 5 filament spools, as can be seen in Figure 2. None of the spools are fully protected from the effects of ambient humidity. Therefore, we decided to create a protective cover made of ABS filament.
The process of creating the dryer is shown in Figure 4. As part of the solution, we chose the option of manual measurement so that we could create a model exactly according to our ideas. The entire dryer will be attached to the filament spool holder, which is shown in Figure 3.

Fig.3 Filament holder

The 3D model was created using SolidWorks software. We created the model from three parts:

- supporting part,
- closing part,
- silica gel basket.

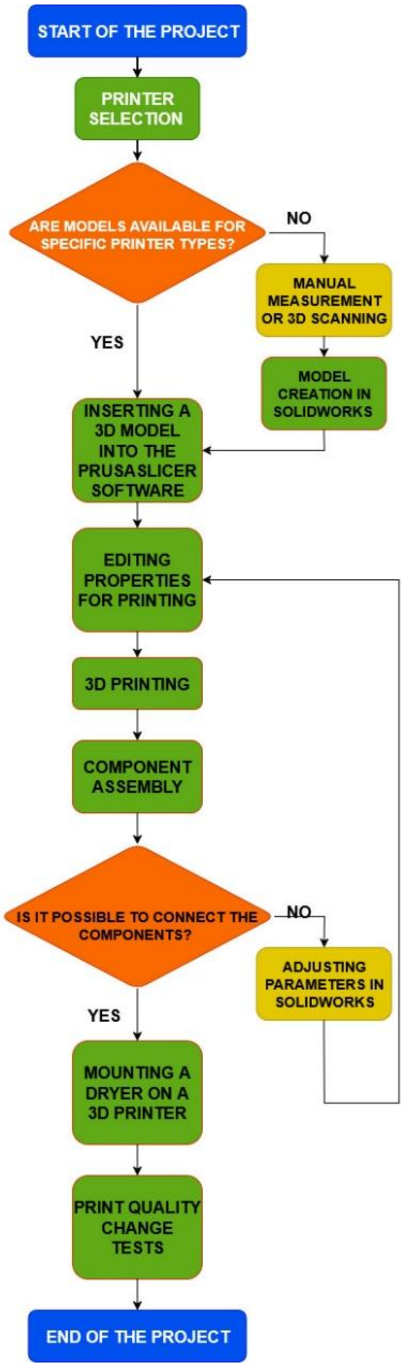

Fig.4 Flowchart for building a dryer for Prusa XL

The supporting part has an opening into which a temperature and humidity meter can be inserted after pressing. Using stops, the meter is fixed in place above the filament reel and thus effectively monitors the humidity inside the dryer. To prevent the filament from meeting the surroundings, an opening is created in the support part, into which a PTFE tube is inserted to prevent contact.

The closing part serves as a lid for the dryer. This lid does not have any additional openings. The entire structure is assembled using neodymium magnets.

The last part, the silica gel basket, will be part of the closing part. There will be additional magnets inside this part, and there will also be magnets on the basket to hold the assembly in place. The parts in SolidWorks are shown in Figure 5.

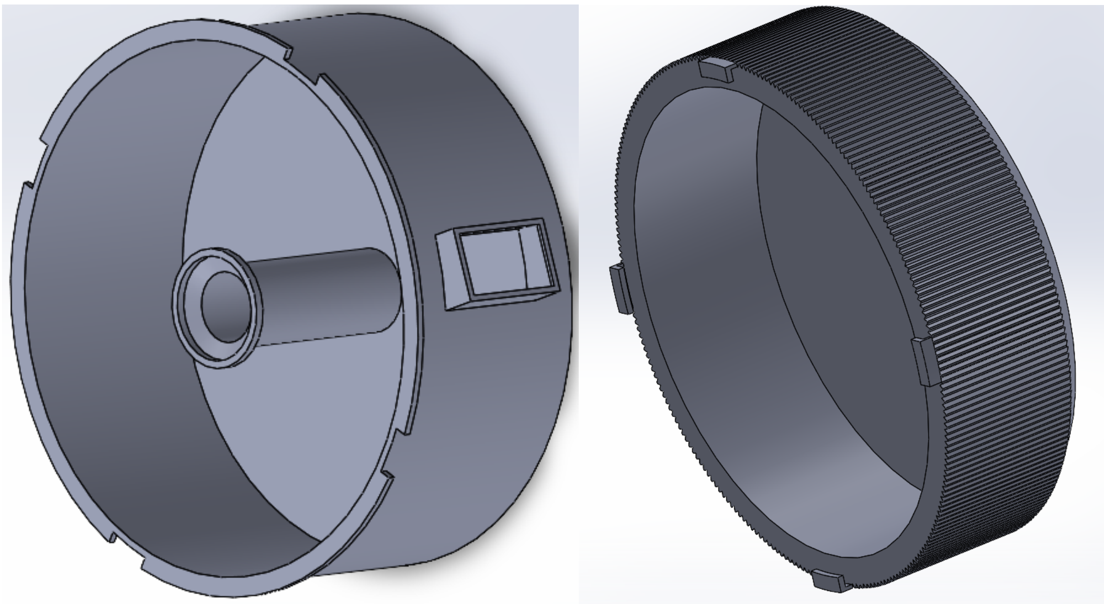

Fig. 5 Dryer model in SolidWorks

Conclusion

Research has shown that moisture absorption is a critical factor negatively affecting 3D printing with thermoplastic filaments. The implemented solution using silica gel in a custom-designed dryer effectively eliminates this problem and improves the quality and mechanical properties of printed parts. The main advantages include low cost, reusability, and compatibility with commonly used printers. Future research may focus on optimizing the dryer geometry, testing alternative desiccants, and integrating automated monitoring systems.

Acknowledgments

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ANALYSIS OF THE IMPACT OF SELECTED GEOMETRIC SPECIFICATIONS ON THE EVALUATION OF THE EFFECTIVENESS AND RELIABILITY OF THE PRODUCT VERIFICATION PROCESS

Mário DRBÚL – Jaromír MARKOVIČ – Richard JOCH – Jozef BRONČEK – Miroslav CEDZO – Alžbeta BRILIAKOVÁ – Jozef MRÁZIK

Abstract: The growing demands for product accuracy in the global market require a re-evaluation of metrological procedures and the implementation of new verification methodologies. A key element is ensuring the uniformity of product verification using the language of geometric product specification (ISO GPS) and the implementation of coordinate measurement techniques. These technologies eliminate human error and support the automation of measurements, which increases the accuracy and reliability of results. The experimental measurements carried out in this study were performed in accordance with the latest knowledge in the field of geometric product specification and with an emphasis on compliance with the principles of metrological traceability. The aim was to verify the extent to which the implementation of modern digital metrological procedures contributes to increasing the accuracy and reliability of measurements while supporting the systematic integration of measurement processes into a digitally connected production chain.
Keywords: Geometrical product specifications (GPS), Product verification process, Metrological analysis, Accuracy and reliability evaluation, Coordinate measuring machine (CMM)

Introduction

Increasing market demands for dimensional and geometric accuracy of products pose a major challenge for metrological and quality processes in manufacturing companies. [2] With the growing complexity of products, shorter production cycles, and increasing automation and digitization of production, there is a growing need to implement advanced metrological approaches that enable accurate, objective, and repeatable verification of product conformity with design documentation and technical specifications. [3] Quality departments are forced to reevaluate conventional methods of measurement and verification of measuring instruments and, at the same time, seek new methodologies that take into account the modern principles of geometric product specification (ISO GPS) defined in the ISO GPS set of standards. These principles ensure the unambiguous determination of geometric requirements for products in terms of shape, dimensions, orientation, position, and runout, which are key to the proper functioning of products and assemblies. [3–5]

In a globally interconnected industry where confidence in measurement accuracy directly affects business relationships and the international competitiveness of companies, ensuring complete metrological traceability is becoming a necessity. [6] Measuring equipment, especially length gauges and coordinate measuring machines, must be calibrated regularly and their measurements must be linked to national or international standards to ensure their metrological traceability. This traceability is one of the main pillars of quality management systems according to standards such as ISO 9001 and ISO/IEC 17025. [1, 3, 6] Modern metrology systems today must reflect developments in Industry 4.0, which brings together physical and digital systems, the use of the Internet of Things (IoT), big data, and artificial intelligence. In this context, metrology is changing from a passive control tool to an active element of the production chain, enabling real-time identification of deviations, optimization of production processes, and feedback to the quality management system.[7, 8] The application of coordinate measuring machines (CMM) plays a special role in current metrology practice, enabling accurate measurement of three-dimensional objects using contact or non-contact sensors.[9] These devices provide high repeatability and minimize subjective errors caused by the human factor. In addition, thanks to integration with specialized metrology software, it is possible to perform complex analyses of measured data, perform automatic comparisons with CAD models (so-called model-based definition), and generate objective reports on the conformity of products with their drawing documentation.[3, 10, 11]

CAD model for verification process

A 3D model of a test sample designed for measurement on a coordinate measuring machine (CMM) was created for experimental verification of measurement accuracy. The sample was designed to contain various geometric elements – planes, cylindrical and conical surfaces, as well as straight and curved edges. These elements allow for comprehensive verification of measurement accuracy in different directions and spatial orientations.

Fig. 1 shows the test sample model created in a CAD environment. The model also includes a hole with a nominal diameter of 40 mm, which was selected as a reference element for experimental measurements and subsequent accuracy evaluation. This hole is an important geometric element that allows for the analysis of measurement accuracy in both the axial and radial directions.

When designing the model, consideration was given to the need to ensure the rigidity of the sample and sufficient access of the measuring contact to the individual elements. The model was then exported to a format suitable for creating a measurement program in the CMM environment.

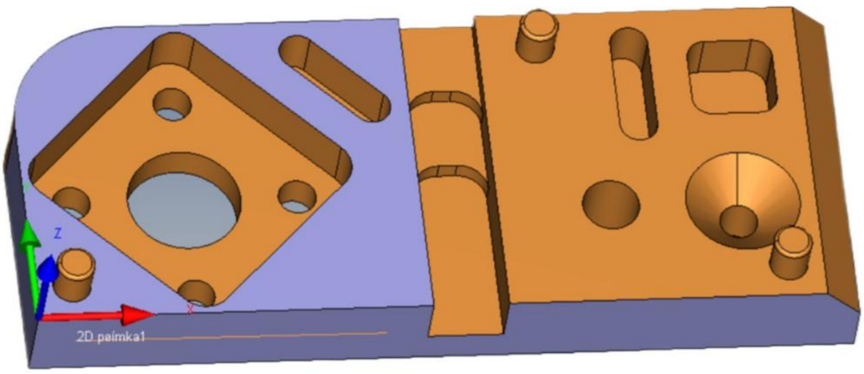

Fig. 1 CAD model in the CALYPSO program environment

Based on the created 3D model, a technical drawing of the test sample was prepared, which contains all nominal dimensions, reference axes, and defined geometric tolerances. A detailed view of the drawing is shown in Fig. 2.

The drawing shows a hole with a diameter of Ø 40 mm, which was the subject of measurement and evaluation of deviations. This hole was measured within a defined coordinate system and its position was determined in relation to the reference surfaces of the sample.

The technical drawing served as a basis for production control and programming of the measurement cycle in the CMM environment. The drawing clearly defines the basic reference elements according to which the sample is aligned in the measuring space. In addition, the drawing contains the layout of the measuring points and the dimensions necessary for assessing dimensional and shape accuracy.

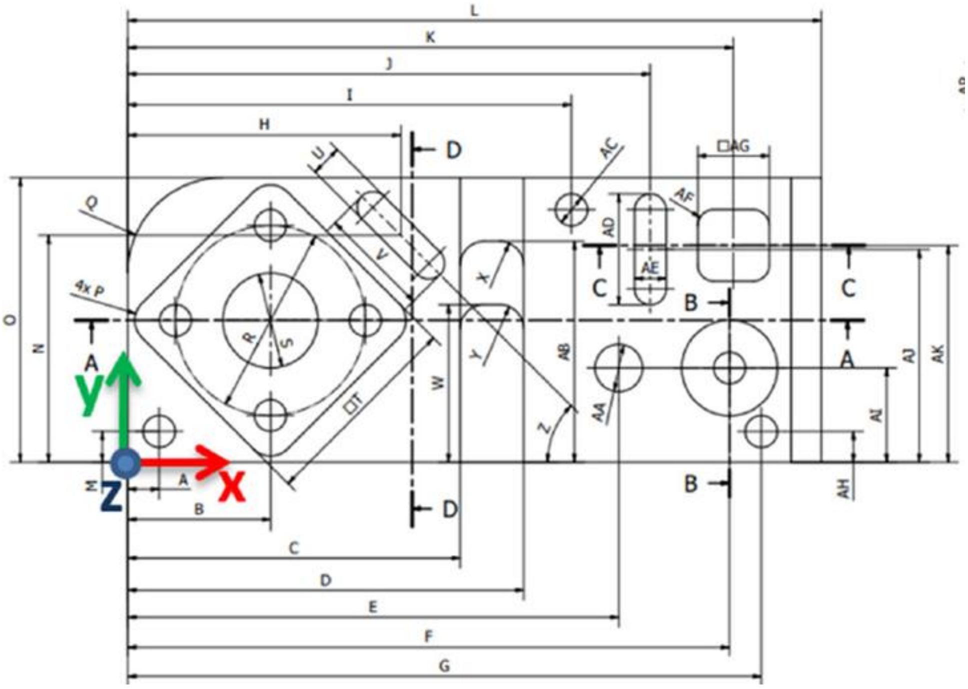

Fig. 2 Artifact verification proposal

The model and drawing of the test sample, shown in Fig. 1 and Fig. 2, form the basis of the experimental methodology. The precise definition of the 40 mm diameter hole allows repeatable measurements to be made and results obtained using different measurement strategies to be compared. Thanks to the precise processing of the CAD model and drawing documentation, it is possible to ensure a uniform reference base for evaluating measurement accuracy and analyzing geometric deviations.
All measurements were performed on an Eclipse Zeiss 3D measuring machine (MPETHP = (4.2+L/200) µm) with the CALYPSO operating program. The measuring machine was equipped with a passive VAST XXT head, a TL3 magnetic plate, and a 1 mm diameter touch tip. The environment in which the measurements were performed was in accordance with STN EN ISO 1 with a temperature instability tolerance of ±1°C.

Taking into account the geometric shape of the element when verifying the dimension
When evaluating the functional dimensions of technical components, it is extremely important to take into account their actual geometric shape, which often deviates from the ideal (theoretical) geometry defined in the design documentation. To ensure the most accurate representation of the actual surface of a component, continuous extraction – scanning – has proven to be an effective and accurate metrological technique. This method is based on collecting a dense network of data points from the surface of the part using contact or non-contact sensors (e.g., optical, laser, or contact probes of CMM devices). Scanning allows the creation of a detailed surface cloud model that captures minor deviations, irregularities, and

undulations, providing a highly accurate digital representation of the actual surface of the measured object (Fig. 3).

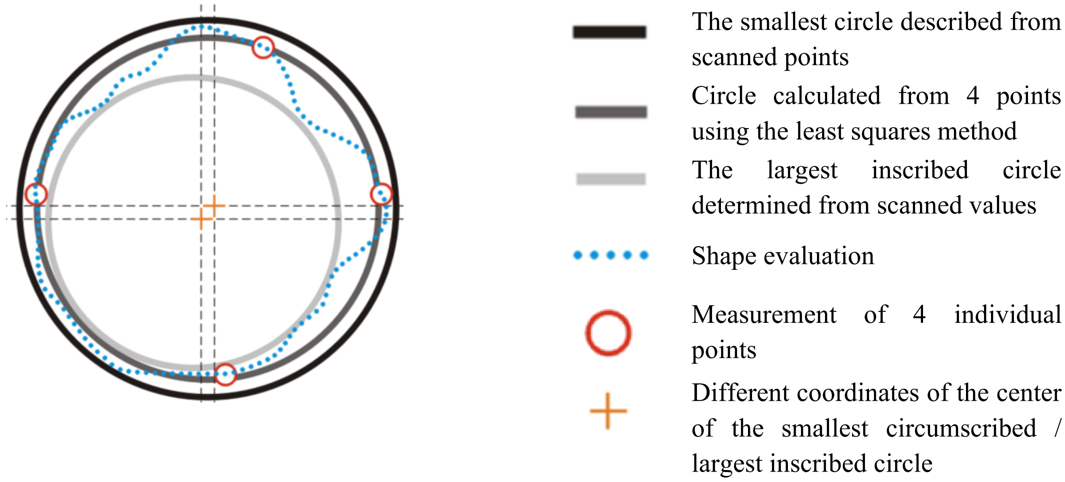

Fig. 3 Influence of discrete and continuous measurement on the methodology of association (approximation) of the geometric element circle

A significant advantage of this method is higher repeatability and stability of results compared to the point (discrete) measurement method, where the result is largely dependent on the selection of specific measurement points. Continuous scanning minimizes the risk of subjective influence on the measurement by the operator and ensures that the resulting model contains sufficient information for reliable analysis of functional and geometric properties. The acquired point cloud serves as input for the approximation of ideal geometric elements such as planes, cylinders, cones, or spheres. The approximation is performed using mathematical methods – most often the Least Squares Method or other optimization algorithms that minimize the deviations between the actual and ideal shapes (Figs. 4 and 5).
Geometric element cylinder/circle and their shape deviations:

- (LSCY) – A reference cylinder/circle is superimposed on the scanned zone using the least squares method.
- Minimum circumscribed cylinder (MCCY) – The smallest possible cylinder circumscribed around the scanned area forms the reference cylinder/circle. It is used to measure external surfaces.
- Minimum radial distance (MZCY) – The scanned zone is represented by two concentric cylinders/circles (reference zone) with the smallest possible difference in radius.
- Maximum inscribed cylinder (MICY) – The largest possible cylinder/circle inscribed in the scanned area forms the reference cylinder/circle. It is used to measure internal surfaces.
- Tangent element – in accordance with ISO 5459 – geometric bases.

Ostatné geometrické prvky je vhodné vytvoriť metódou najmenších štvorcou z dôvodu ich geometrickej stability napr. oblúky, free form.

Fig. 4 shows the deviation values for three different measurement methods (the cage method, cross-cut method, and method of forming straight lines) and three samples examined (LSCY, MZCY, and MCCY).

The results show that the MCCY sample exhibits the highest deviation values in all cases (7.8–7.9 µm), indicating its lower dimensional accuracy compared to the LSCY and MZCY samples. The lowest values were achieved with the straight line formation method, where LSCY and MZCY achieved values of 4.4 µm and 4.3 µm.

In general, it can be observed that the straight line formation method shows the smallest deviations, while the cage and cross-cut methods provide comparable results with higher deviation values.

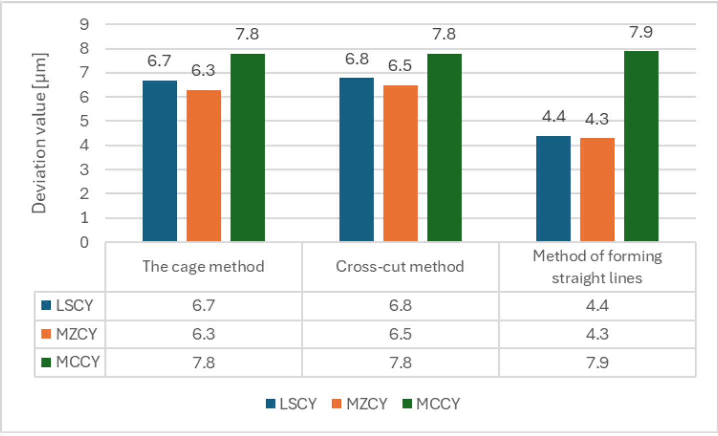

Fig. 4 Example of the influence of the extraction strategy of the surface of a geometric element, a cylinder with a diameter of 40 mm, on the geometric deviation of the shape (according to Fig. 2, parameter S) (Number of scanning points: 5200, Filter type: low-band Gauss, scanning speed: 2 mm/sec. UPR: 150, verified diameter: ϕ40)

The figure 5. shows a comparison of the average deviation values obtained using three different processing methods – LSCI, MZCI, and MCCI – applied to the three analyzed parts. The values are expressed in micrometers [µm].

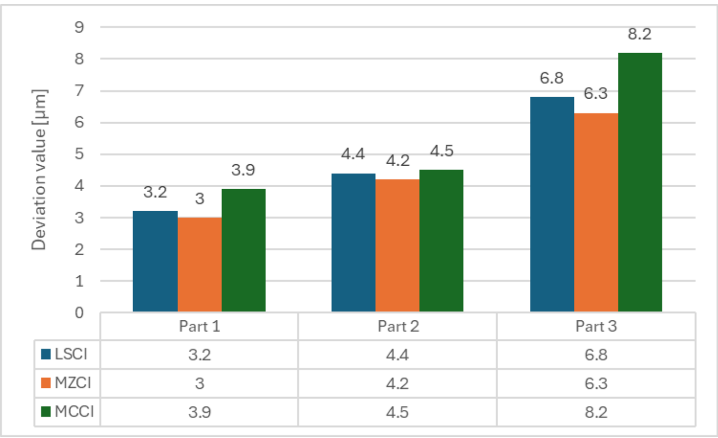

Fig. 5 Example of the influence of the approximation method on the evaluation of geometric roundness deviation (according to Fig. 2, parameter S) (Number of sampling points: 1,300, Filter type: low-band Gauss, UPR: 150, verified diameter: ϕ40)

The graph clearly shows that individual methods provide different levels of measurement accuracy. The MZCI method shows the lowest deviation values in all analyzed cases, which indicates its higher stability and consistency of results. Conversely, the MCCI method achieves the highest deviations, which may indicate its higher sensitivity to changes in input conditions or less robust data processing. The LSCI method lies between these two approaches and represents a compromise between accuracy and stability.

Such a comparison allows for a better understanding of the impact of individual correction algorithms on the final measurement quality and provides a basis for selecting the optimal method depending on the required accuracy and experimental conditions.

Conclusion

The right choice of extraction strategy has a fundamental impact on the resulting accuracy and relevance of the measurement, and thus on the overall quality of the component inspection. The value of the resulting geometric shape deviation is influenced by a number of factors. These include the strategy used to extract the actual shape of the relevant geometric element, the measuring systems used, and the tip finish of the sensors. The selection of a suitable and optimal approximation also depends on the function of the measured component.

In conclusion, the application of the continuous surface extraction method represents an important step towards ensuring a more accurate and reliable interpretation of the actual dimensions of components in modern manufacturing processes. In combination with GPS standards, it forms the basis for the high-quality and effective implementation of metrological processes in accordance with Industry 4.0 requirements.

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SIMULATION MODELING AS A TOOL FOR OPTIMIZING PRODUCTION PROCESSES

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Abstract: Simulation-based optimization is a vital method for enhancing manufacturing processes. This case study explores the design, simulation, and implementation of process improvements in a metalworking company. Using collected production data, key bottlenecks were identified and addressed through the integration of conveyors and overhead cranes. The outcomes highlight notable gains in productivity, reduced material handling times, and improved production ergonomics. This study underscores the practical value of simulation modeling in optimizing industrial processes and supporting investment decisions.

Keywords: *optimization, productivity improvement, simulation, bottleneck analysis*

Introduction

In the context of modern industrial production, the pressure to utilize production resources efficiently, minimize costs, and increase the flexibility of production processes is constantly increasing. The ability of manufacturing companies to optimize their processes often determines their competitiveness in the market. One of the most effective tools to support the optimization of production systems is simulation modeling. It allows testing various scenarios of process adjustments before their introduction into real production, thereby minimizing the risk of inefficient investments [1, 2].
This study aimed to analyze and optimize the production process in a company that focuses on the processing of metal components. Using simulation modeling, bottlenecks in the process were identified, optimization measures were proposed, and these were subsequently implemented and evaluated in practice [3, 4].

1. Methodology

The initial phase of the project was the detailed collection of data on individual production operations, handling times and material movements throughout the entire production process [5]. The data obtained included:

• times of individual operations (cutting, milling, welding, packaging, etc.),
• downtime between operations,
• duration of manual material handling,
• logistical transfers between workstations [6].

From the collected data, an accurate 3D simulation model of the production hall was created in the Process Simulate software (Fig. 1).

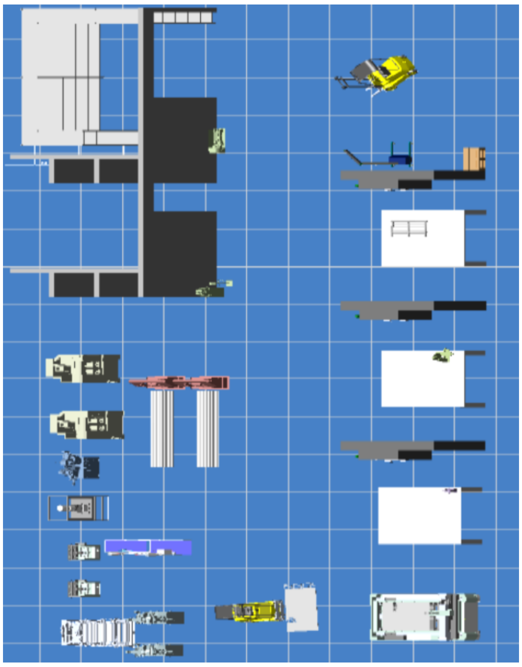

Fig. 3 Simulation model of the production hall

After running the baseline simulation, it was found that the main problems were:

• long waiting times between operations (Fig. 2),
• uneven utilization of workstations,
• excessive manual handling times,
• accumulation of material in selected locations [7].

The most significant bottlenecks included the transfer of semi-finished products between workstations and the inefficient distribution of machines within the production hall [8].

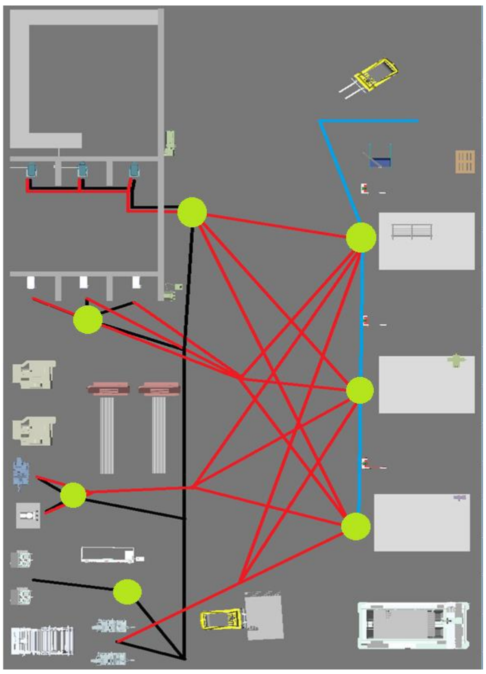

Fig. 4 Identifying bottlenecks

2. Proposal for optimization measures

Based on the identified weaknesses, we proposed improvements such as adjusting the work sequence, optimizing the material flow and improving coordination between stations. We analyzed each improvement thoroughly using simulation. Our proposal consisted of implementing conveyors at several stations such as: saws, shears, press, milling machines, lathes, drills, welding equipment, material burning machine and gantry cranes at welding equipment.
Based on the simulation results, specific measures were proposed:

- Implementation of belt conveyors (Fig. 3) – automatic conveyors were included between the cutting, milling and welding workstations in order to eliminate manual material transfers.

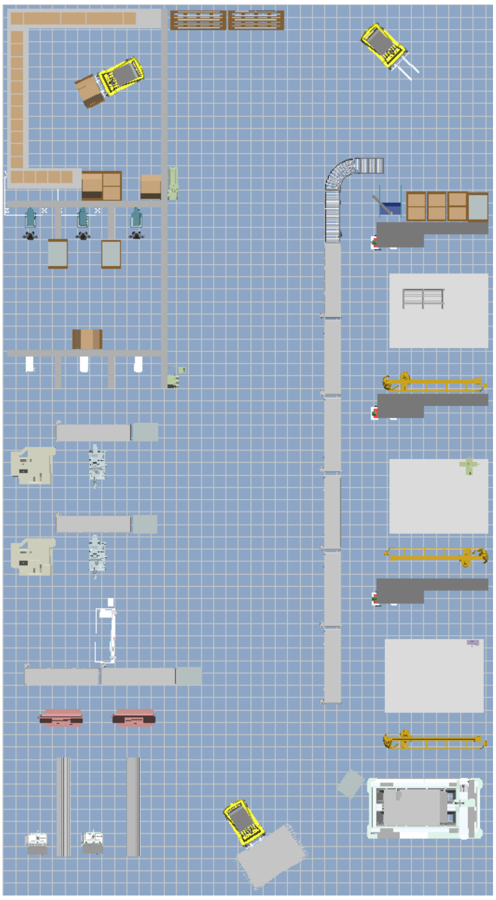

Fig. 5 Implementation of conveyors belt

- Installation of gantry cranes – in welding workplaces, they enable efficient handling of heavy products without the need for additional workers.
- Adjustment of the hall layout – optimized arrangement of machinery minimized distances between subsequent operations.

The company approved the improvements, and we then implemented them in a real environment. During the implementation, we constantly monitored their effectiveness and adjusted them as needed based on actual results.

The implementation of conveyors and cranes proved to be a key solution for optimizing our processes. These improvements allowed us to effectively manage material flow and improve work coordination between our workstations. The addition of conveyors allowed us to transport materials more smoothly and faster, which led to increased efficiency and speed in our production processes.
When running the simulations, we experimented with different workstation layouts. The best results were achieved with a layout where we placed the material splitting and cutting machines right at the entrance, followed by 20-ton sheet metal shears, CNC lathes, milling machines and bench drills. We added conveyor belts to individual stations to quickly divide the material and transport it for packaging and export. We added gantry cranes to the welding tables, which made the process of folding and moving material more efficient (Fig. 4).

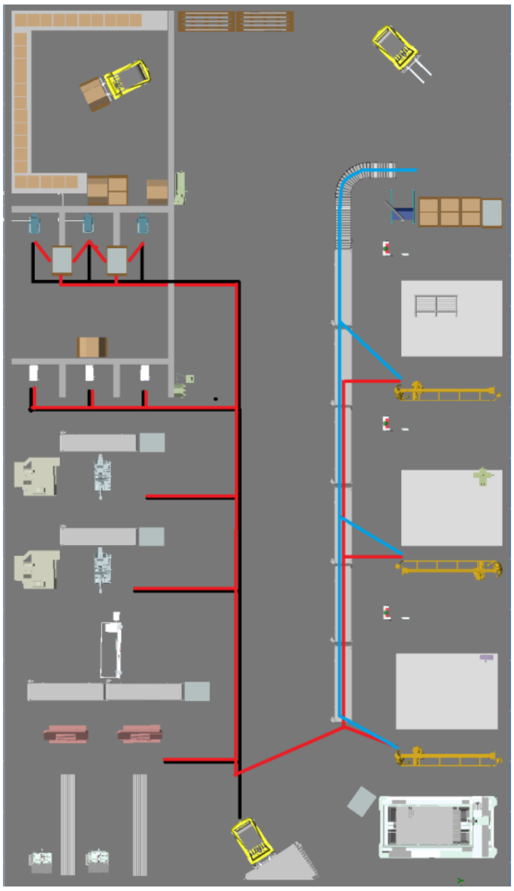

Fig. 6 Simulation model of the hall after optimization

These improvements have allowed us to use resources more efficiently, speed up workflows, and improve the overall performance of our company. Tracking results and adjusting processes as needed has allowed us to achieve optimal results and ensure the successful implementation of improvements into our production environment.

3. Simulation evaluation of measures

Simulation results before optimization

The original model showed the following operation times (Table 1):

Tab. 4 Production time before optimization

Operation	Time (min)
Incoming inspection	30
Manual material division	60
Dividing, cutting, drilling	90
Transfer of semi-finished products to welding	60
Welding	150
Grinding	90
Transfer to packaging	30
Packaging	30
Total for 10 pcs	**9 h (540min)**

Simulation results after optimization

After implementing the conveyors and gantry cranes, we have seen significant improvements in the time sheets related to the material transfers between individual workstations. Specifically, we have found that the times required to transfer material have decreased by more than 45% compared to previous simulations (Table 2).
These improvements in time sheets are the result of the efficient use of the conveyors and gantry cranes, which have enabled faster and more reliable material transfer between individual points in the production process. This has not only contributed to the reduction of waiting times and delays, but also to the overall increased efficiency and performance of our production operations.
The evaluation of the results has shown that the implementation of the conveyors and gantry cranes has been successful and has contributed to a significant improvement in the time sheets in our production processes. These positive results confirm the value of these improvements and their significant contribution to the optimization of our company.

Tab. 5 Production time after optimization

Operation	Time (min)
Incoming inspection	30
Conveyor material distribution	30
Dividing, cutting, drilling	90
Transfer of semi-finished products for welding by conveyor	30

Welding	150
Grinding	90
Transfer to packaging by conveyor	10
Packaging	40
Total for 10 pcs	**7 h 50 min (470 min)**

The annual benefit can also be expressed based on total annual production:

Before optimization:

$$220\text{ h}: 0.9\text{ h/piece} = 244.44\text{ pieces/month}$$

After optimization:

$$220\text{ h}: 0.783\text{ h/piece} = 281.58\text{ pieces/month}$$

Difference per month:

$$281.58 - 244.44 = 37.14\text{ pieces}$$

Annually (x12):

$$37.14 \times 12 = 445.68\text{ pieces/year}$$

The annual increase in production is approximately +445 pieces (Table 3).

Tab. 6 Effect of the achieved change

Indicator	Value
Reduction of production to 1 piece	from 54 min. to 47 min.
Increase in monthly production	from 244 to 281 pcs
Annual increase in production	+ 445 pcs
Reduction in physical effort	- 100% manual handling
Reduction in downtime between operations	- 85%
Reduction in transfer time	by more than 45%

Our optimization of work using conveyors and gantry cranes has proven to be very successful. We have achieved a significant improvement in time parameters, which has a positive impact on the efficiency, productivity, and competitiveness of our company. In addition, the solution

is universal and expandable, which opens the possibility of its further use and expansion to other companies.
Overall, it can be stated that our optimization represents a significant step forward and brings great potential for further improvements and the development of the company.

Conclusion

The results clearly show that simulation models can be used to accurately quantify the expected effects of optimization already at the planning stage. Such an approach significantly reduces the risk of erroneous investments. The implementation of measures led not only to an increase in productivity but also to a reduction in the physical effort of workers, a decrease in the rate of handling accidents, and a smoother production process [9].
Process simulation using the Process Simulate tool has demonstrated high added value for managerial decision-making. The combination of technical optimization (conveyors, cranes) and precise simulation verification made it possible to achieve:

• a reduction in production times by 13% per piece,

• an increase in productivity by 15% per month,

• a significant increase in work safety and ergonomics.

At the same time, the results point to the universality of the proposed solutions, which can also be applied in other manufacturing companies with a similar nature of production. This case confirms that even with relatively simple interventions in the field of handling technology, significant improvements in production performance can be achieved.

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SIMULATION VERIFICATION OF THE DESIGN FOR IMPROVING THE EFFICIENCY OF A PRODUCTION UNIT

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Abstract: Introducing changes in the production process that are necessary for innovation often causes problems, such as production interruptions. These changes are often time-consuming, costly, and the outcome can be uncertain. Therefore, it is important to thoroughly verify these changes first, since the introduction of modern technologies does not mean automatic success. In the field of production planning, computer simulations play a key role because they allow predicting the behavior of the system before it is launched. Simulation programs not only offer 3D visualization and animations of machines, workers, and products, but also provide analytical tools that serve to verify the proposed solutions. This work will focus on a manufacturing company to simulate the current production of products. Subsequently, a second simulation was created in which we applied the planned innovative technologies. We will analyze the created simulation model of production adjusted by innovations and compare it with the model of current production. We will compare these simulation models and evaluate the benefits of the proposed innovations.

Keywords: simulation, verification, production layout

Introduction

Simulation is an attempt to model a real or hypothetical situation on a computer to study how a system works. By changing the variables in the simulation, it is possible to predict the behavior of the system. It is a tool for virtually investigating the behavior of the system under study. To create a simulation of a specific situation in the production process, we will use the Plant Simulation program from Siemens. The Plant Simulation program also allows you to create your own 3D models, but this process is time-consuming, and the creation tools are quite basic. However, it supports the import of models in various formats, such as IGES, STEP, VRM,L, and NX. Therefore, we decided to use the SolidWorks CAD program to create 3D models.

Production process and its description

The company is a major manufacturer in the field of mechanical engineering, specializing in the production of air tanks for braking systems of rail vehicles. In addition, it also focuses on the production of semi-trailer frames for road trucks. In this article, we will deal with the production of air tanks. Production consists of the following operations:

Bottom production - when producing the bottom, it is first necessary to produce a blank, which is then shot blasted and bent into the required shape.

Shell production - when producing the shell, it is first necessary to cut the sheets into the necessary shapes, then the sheets are punched and bent into the required shape. Then the shell is welded, then a hole is drilled into which a threaded coupling is then welded.

Connecting the shell to the bottom - when the bottom and shell are ready, welding and finishing of the finished product takes place. When the entire product is completely welded, it is necessary to weld a label with the serial number and technical parameters to it.

Painting of products – after the entire product is completed, painting begins. First, a base coat is applied to the product, which after painting passes through a post-drying chamber. After applying the base coat, a surface treatment is applied.

Fig. 1 Dosušovacia komora po lakovaní

Analysis of the status of the issue

The company is currently facing unnecessary costs in the overall production of air tanks, which arise due to inefficient machine layout and inappropriately solved internal logistics. A significant problem is the complicated and time-consuming transport of sheets between workplaces, which is also exacerbated by the insufficient use of the plasma cutting machine located directly in the main production hall.

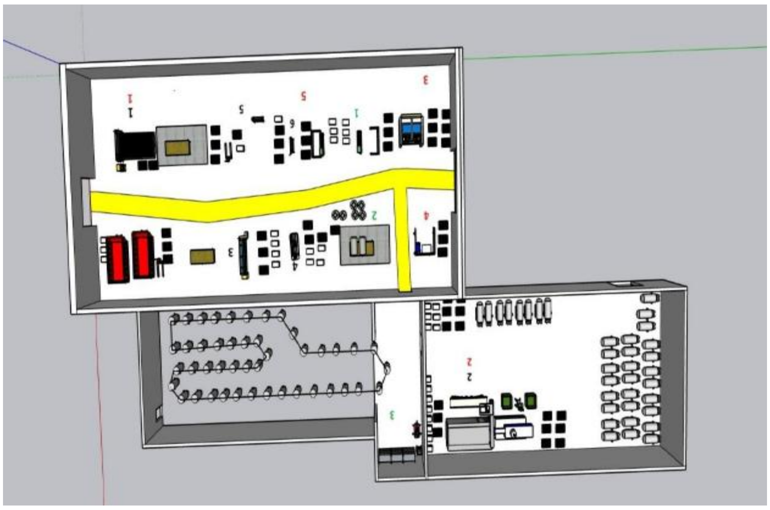

Fig. 2 Current status in production

In the Plant Simulation program, we modeled the entire production hall, into which we gradually inserted individual operations. This simulation was able to bring the entire production closer to us with a detailed procedure and with real factors influencing this process. Each operation was supplemented in the simulation with technical and time parameters corresponding to real production

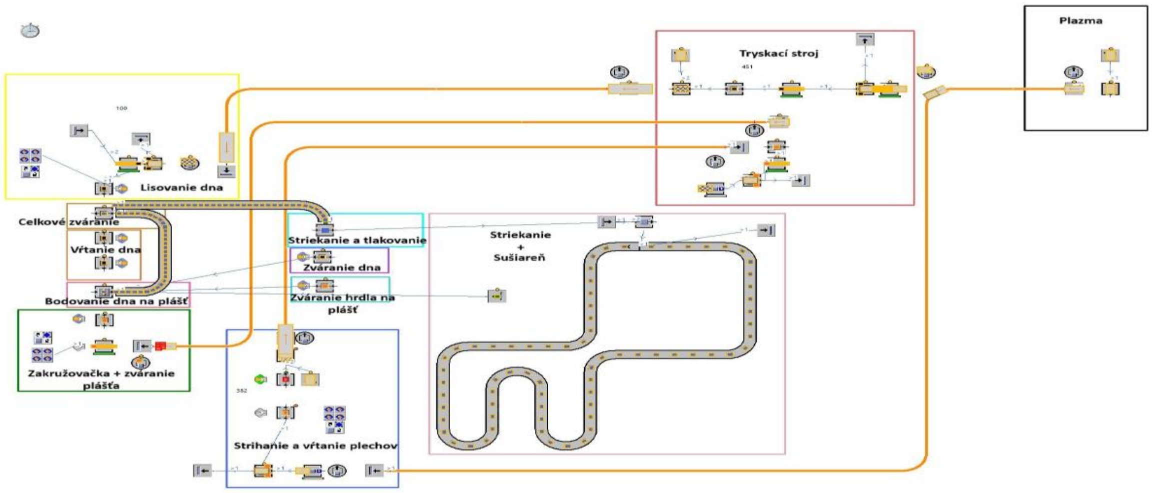

Fig. 3 Current status in production 2D simulation

Production improvement proposal

In SketchUp, we modeled a production hall with a new arrangement of machines, which we designed to streamline production and shorten production time. After selling the old plasma, which is currently not used, is extremely large and inefficient for this production, we will get space to purchase a new plasma, which will save us time transporting sheets from a remote workplace, and also save the costs of this transportation and, at the same time, the costs of the employee associated with this transportation. Given that the old plasma located in this hall is very large, after its sale, space will be created that will allow us to move the blasting machine to this location and save time transporting sheets to the adjacent hall. This blasting machine needs to be separated by a wall and provided with appropriate extraction.

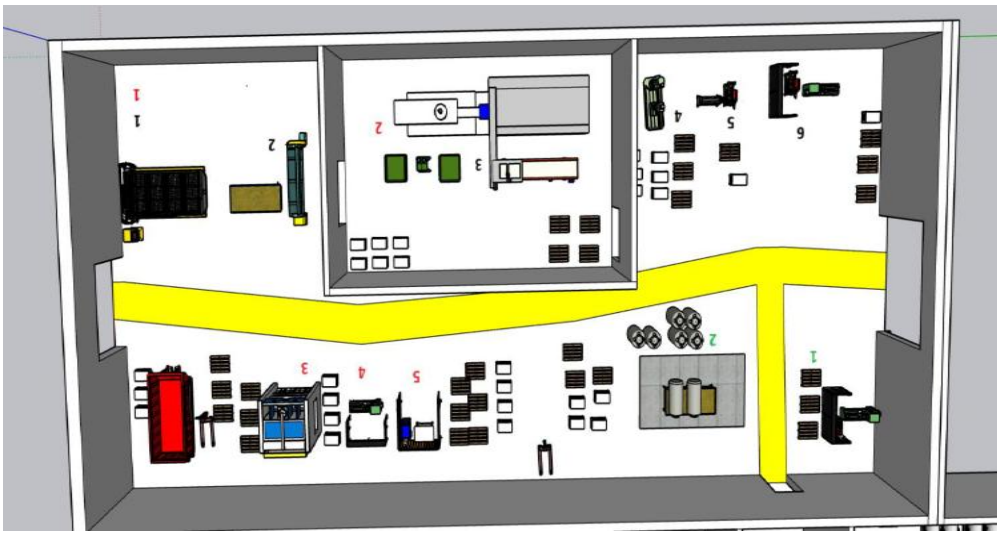

Fig. 4 Design of new equipment layout

By properly arranging the machines and moving the blasting machine to the main hall, we have gained space in the warehouse for larger stocks of materials and larger stocks of air tanks. With larger stocks in the warehouse, the company will be able to withstand possible machine failures in production. For simulation verification, we used the Siemens Tecnomatrix Plant Simulation software, which enables modeling, simulation and optimization of production and logistics processes. The model created in this environment meets the parameters and the structure of the analyzed system itself, as described in the previous chapters. When creating the model, real input parameters, material flow and also logistical constraints were included in the simulation.

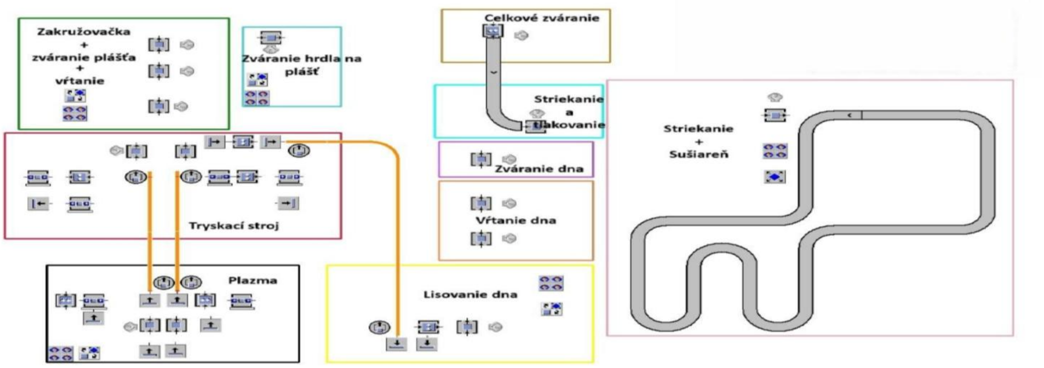

Fig. 5 Simulation of the designed state in the production process

The simulation allowed us to visualize the production system in more detail. Based on the results, we can say that the designed system is effective and meets the expectations proposed in the theoretical part. In the designed workplace, we achieve production with a difference of 222 pieces of products.

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Drain	paleta1	1:22:32:00.3999	44	0	74.95%	25.05%	0.00%	25.86%	
Drain1	vozík	23:16:00.5699	45	0	49.03%	50.97%	0.00%	0.00%	
Drain3	vozík	22:37:11.3415	47	0	49.37%	50.63%	0.00%	0.00%	
Drain4	paleta2	1:05:21:51.8496	47	0	88.35%	0.07%	11.58%	11.32%	
Drain6	vozík_plech	3:12:06:10.6445	11	0	46.87%	53.13%	0.00%	0.00%	
Drain2	vzduchojem	2:17:04:27.8115	1130	2	2.06%	97.94%	0.00%	1.29%	
Drain5	paleta1	4:18:59:45.1088	98	0	11.84%	4.13%	84.04%	4.77%	
Drain7	vozík_zasobovanie	17:56:36.8463	59	0	49.41%	50.59%	0.00%	0.00%	
Drain8	paleta1	20:05:08.0547	59	0	16.72%	45.20%	38.09%	16.72%	

Cumulated Statistics of the Parts which the Drain Deleted

Simulation results of the original production process

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Drain	paleta1	1:23:15:51.9098	55	0	74.98%	25.02%	0.00%	25.66%	
Drain1	vozík	23:36:25.9579	56	0	49.23%	50.77%	0.00%	0.00%	
Drain3	vozík	23:06:45.0986	58	0	49.50%	50.50%	0.00%	0.00%	
Drain4	paleta2	1:13:59:20.0519	58	0	74.43%	0.06%	25.52%	13.59%	
Drain6	vozík_plech	3:15:39:28.5064	14	0	47.56%	52.44%	0.00%	0.00%	
Drain2	vzduchojem	2:18:06:05.9812	1352	2	2.07%	97.93%	0.00%	1.29%	
Drain5	paleta1	6:01:56:00.7004	120	0	9.57%	5.32%	85.12%	3.86%	
Drain7	vozík_zasobovanie	18:19:35.2045	73	0	49.53%	50.47%	0.00%	0.00%	
Drain8	paleta1	22:02:35.5287	73	0	15.22%	41.96%	42.82%	15.22%	

Cumulated Statistics of the Parts which the Drain Deleted

Simulation results of the proposed production process

Fig. 6 Comparison of simulation results

Conclusion

The aim of this diploma thesis was to design and streamline the production of pressure vessels as a final product in the production process. Using a combination of modeling in the 3D SketchUp program and material flow simulation in the Plant Simulation program, we were able not only to plan the project, but also to effectively verify its benefits before its implementation. The investment in a new plasma and modernization of the hall is therefore economically advantageous and technically well thought out in the long term. In addition to increasing capacity, it will also bring better production quality, flexibility and greater competitiveness of the company on the market. The simulation results show that the production process has not only accelerated, but also increased the volume of the final production output. The above facts show that simulation, either as a separate tool or in combination with other software tools, is an effective tool in solving innovation in production processes.

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OPTIMIZATION OF CAD 3D MODELS FOR INTERACTIVE VIRTUAL ENVIRONMENTS

Marián MATYS - Martin KRAJČOVIČ - Martin GAŠO

Abstract: The presented article presents a methodology to ensure compatibility of CAD 3D models in interactive virtual environments. Several issues may occur when converting 3D models created in CAD software to polygon models in virtual reality solutions. The proposed method explains a workflow to fix these problems to potentially save time during development.
Keywords: CAD models, virtual environments, polygon models, 3D model compatibility

Introduction

The cornerstone of faithful virtual simulation of real processes lies in the quality of 3D models. Usage of virtual reality as an educational and visualization tool in industry is becoming increasingly prevalent [1-2]. However, 3D models created in CAD software are based on different principles than 3D models used in interactive virtual environments (polygon models). This questionable compatibility may cause issues during the development process [3-4].
The difference between 3D models created in CAD software (NURBS) and polygon models is that NURBS uses curves and splines, while polygons use flat and straight lines and vertices to create a mesh. NURBS are most often used in engineering models where accuracy is paramount. Polygons create solid planes and shapes by drawing lines between specific vertices. Although various CAD software support export in multiple formats compatible with game engines used to create interactive virtual environments, it is highly likely that issues may occur. The presented article explores options for preparing these 3D models for usage in various VR (virtual reality) applications.

Methodology

Proposed methodology consists of multiple steps that require various software. Fig. 1 shows all the steps.

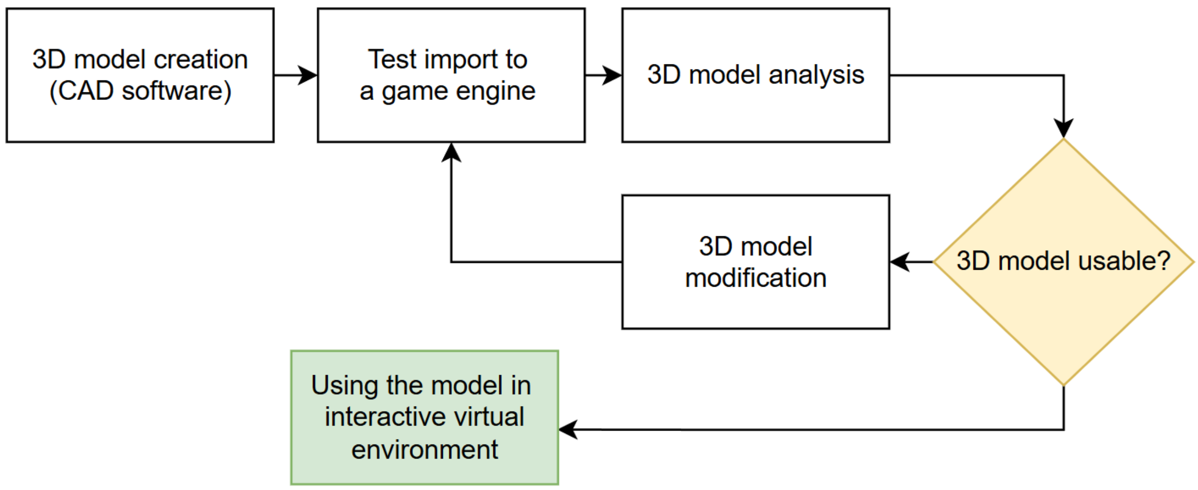

Fig. 7 Proposed methodology [Source: Authors]

For the creation of a CAD 3D model, SolidWorks software was used. Blender and FreeCAD were used for the needed 3D model modifications. Finally, the Unity 3D game engine was used for testing. When trying to import a 3D model created in CAD software, the first issue that may occur is a mismatch of formats.
Some CAD software supports exporting in formats such as ".obj", which can be imported to a game engine; however, some may not offer this option. In this case, additional CAD software can be used, such as FreeCAD, a free software that will not require additional cost. FreeCAD allows users to import most commonly used CAD formats and export them as 3D models usable in interactive virtual environments.
3D models in a compatible format can now be exported to a game engine for 3D model analysis. Exporting a CAD 3D model to a polygon model format will run an algorithm that will transform its structure; this process may cause various issues which need to be identified in model analysis, such as:

- 3D models size mismatch.
- Some surfaces of 3D model not showing correctly.
- Missing textures.
- Overly complex mesh.

With issues identified, 3D modelling software can be used to fix the problems and ensure suitability for an interactive virtual environment. One of the software that can be used is Blender, a free 3D modelling software that has all the tools needed to fix any problem listed above.
For a size mismatch, 3D models need to be scaled to match the real size. The likely culprit is a wrong basic measurement unit in the software settings. If there are parts of the model that are not showing correctly, normals (a vector that is perpendicular to a surface at a given point, indicating the direction the surface is facing) need to be flipped for affected surfaces, which can be done easily in 3D modelling software. The problem with missing textures can likely be fixed in the game engine by providing an external folder or changing the settings for texture loading. Finally, mesh complexity is the most common problem. Even if the model looks fine, it may be composed of a redundant number of vertices (basic 3D model building unit). This adds an unnecessary performance requirement for rendering and may greatly affect the smoothness of interactive virtual environments. 3D modelling software often offers tools to reduce the complexity of a 3D model without affecting its shape.

Application
At the Department of Industrial Engineering, University of Žilina, this method is often used if required 3D models were not built to be used in interactive virtual environments. It is often a much more viable alternative to making the polygon model from scratch. As an example, fig. 2 shows a CAD 3D model that was used as an asset in an interactive manufacturing system visualization.

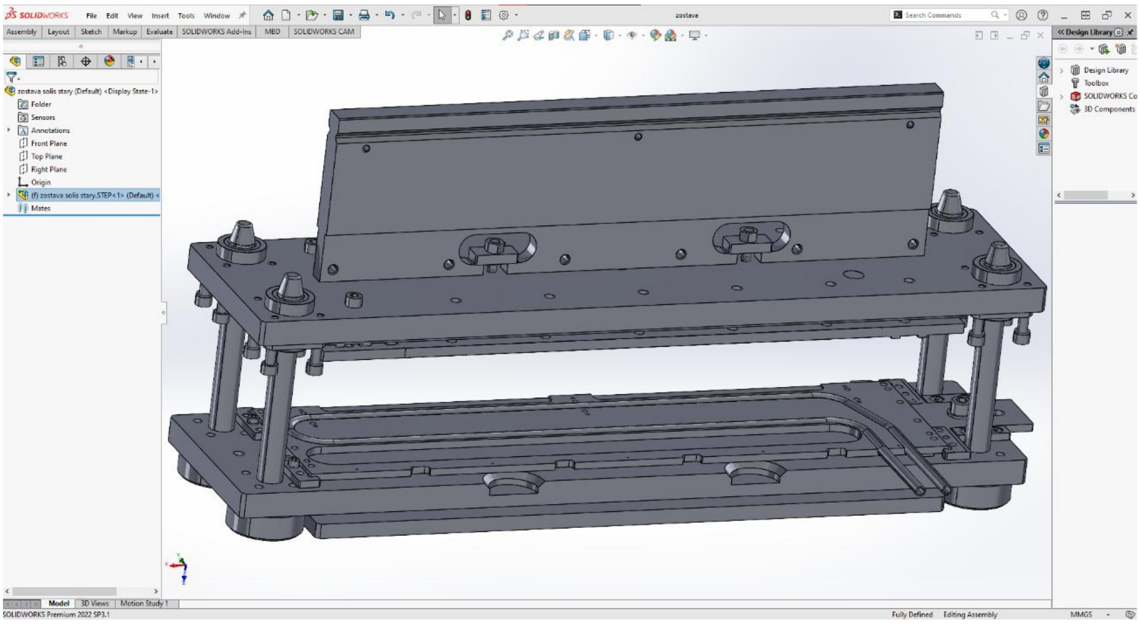

Fig. 8 CAD 3D model [Source: Authors]

Using the presented methodology, this 3D model was modified to be fully compatible for use in VR environments. Test import and analysis showed multiple issues as mentioned in the previous chapter, mainly problems with 3D model size, a few surfaces not showing correctly and model complexity. 3D modelling software Blender was used to fix these problems (fig. 3).

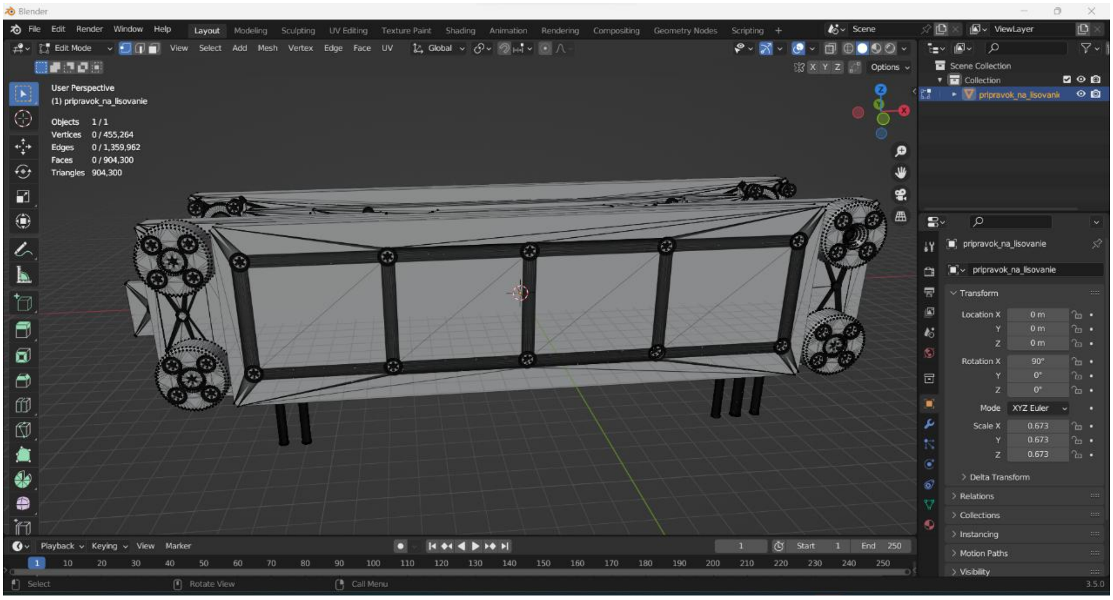

Fig. 9 Model modification [Source: Authors]

After fixing all the problems, 3D model could be imported to Unity 3D game engine as a finalized model. It was added to the 3D model library for creation of interactive and immersive visualization of manufacturing system. Fig 4. shows the creation of its virtual environment and placement of our modified model to the scene. Lowering the model complexity was especially important in this case, because it was placed in many areas of manufacturing system, therefore, it could have a big impact on application performance.

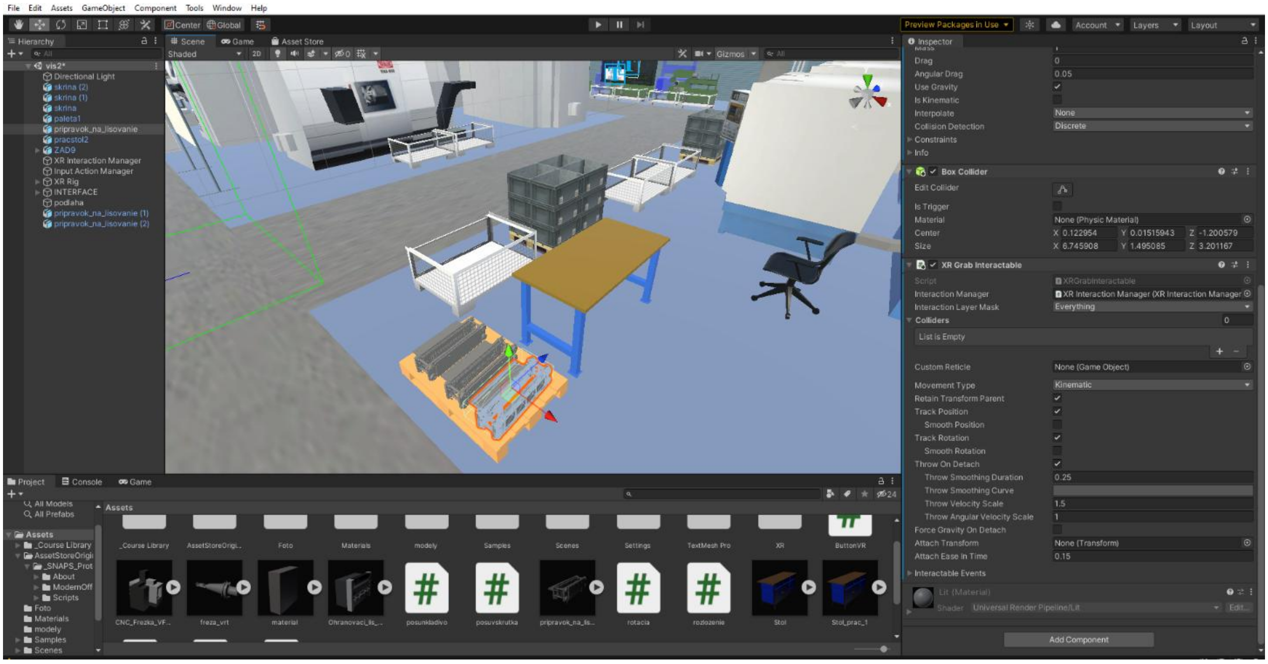

Fig. 10 Creation of virtual manufacturing system [Source: Authors]

After completing the application, players could put on a virtual headset to walk across the virtual manufacturing system. Additionally, they could simulate the material flow between specific operations. The modified model was used for this case. Optimisation of CAD 3D models instead of creation of brand new 3D models reduced the development time and will be applied to different models and projects in the future. Fig. 5 shows the testing of the completed application.

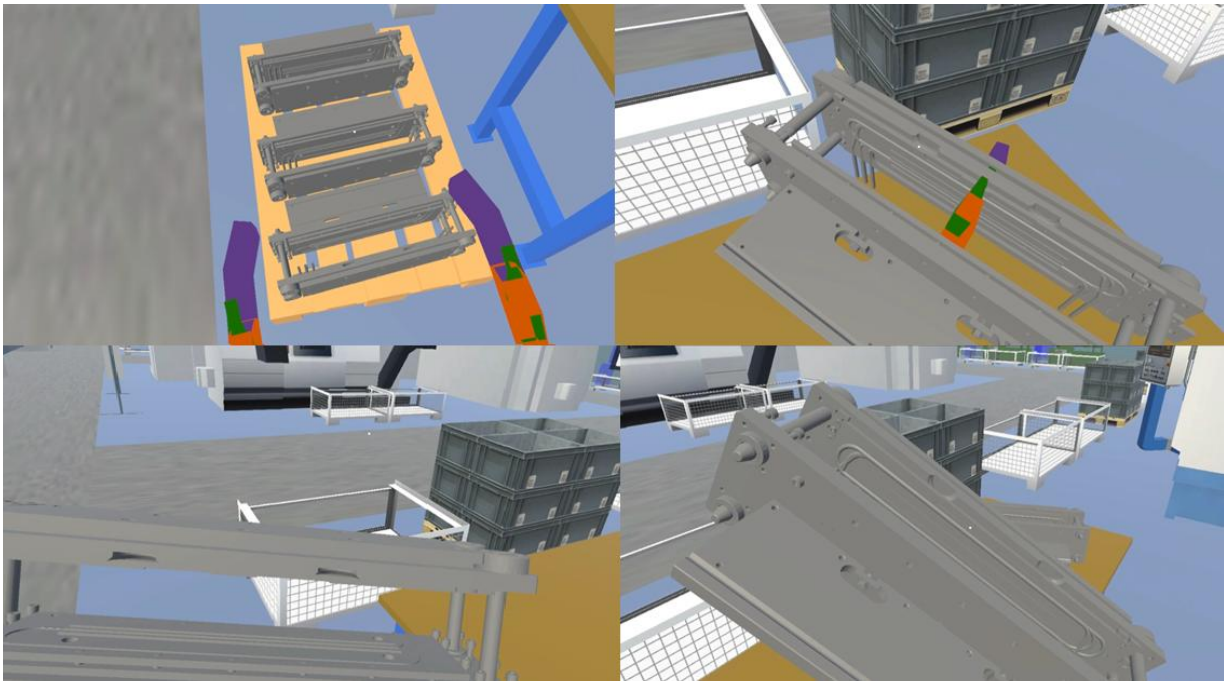

Fig. 11 Aplication testing [Source: Authors]

Conclusion

The benefit of the methodology lies in the proposed unified procedure, the functionality of which has been verified and can be applied to any CAD drawing or model. It allows users to utilise CAD models in digitalisation processes for which they were not designed. This procedure is also easy to use and uses software solutions available for free. The presented solution can be applied in education, mechanical engineering, aviation, healthcare or more.

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SIMULATION-BASED ERGONOMIC ASSESSMENT OF MANUAL WORK USING DIGITAL HUMAN MODELING

Jana KRONOVÁ – Miriam PEKAČÍKOVÁ - Peter TREBUŇA - Marek KLIMENT

Abstract: The integration of digital human modeling and simulation represents a powerful approach to improving workplace ergonomics in modern manufacturing. These tools enable the creation of virtual work environments where employees' postures, movements, and physical loads can be analyzed without interrupting production. Unlike traditional ergonomic assessments, simulations allow proactive testing of workplace modifications, such as adjustable shelves or equipment holders, before implementation. By applying RULA analysis within digital human models, high-risk tasks can be identified and optimized, reducing physical strain and the likelihood of musculoskeletal disorders. The use of these technologies supports safer, more efficient, and more comfortable work environments while minimizing costs and ensuring evidence-based ergonomic improvements.

Keywords: simulation, digital human modeling, ergonomic assessment

Introduction

Human participation remains one of the most critical factors influencing the performance, safety, and efficiency of industrial production systems. Despite the increasing level of automation, humans continue to be responsible for decision-making, control, and execution of complex production operations. An error caused by an operator can, in some cases, lead to serious consequences for both productivity and safety. Achieving maximum efficiency in the interaction between humans and technical systems is only possible when there is an optimal balance between the technical characteristics of machines and the psychophysical capabilities of workers. The discipline that deals with these relationships is ergonomics [1,2].

Ergonomics aims to adapt work systems to human capabilities and limitations, thereby increasing performance and reducing the risk of work-related musculoskeletal disorders (MSDs). In industrial environments, poor workplace design can lead to repetitive strain injuries, fatigue, and long-term health problems [3]. Therefore, ergonomic assessment and optimization have become an integral part of modern production system design.

In recent years, the development of digital human modeling (DHM) and simulation technologies has enabled a significant shift toward *virtual ergonomics*. Digital simulation tools allow for accurate modeling of human postures, movements, and interactions with work environments before any physical implementation takes place. This approach reduces costs, shortens design cycles, and improves workplace safety [4–6].

One of the most commonly used tools for such analysis is Siemens Tecnomatix Process Simulate Human, which integrates digital human models into virtual manufacturing environments. The software enables motion analysis, posture evaluation, and ergonomic risk assessment using standardized methods such as RULA (Rapid Upper Limb Assessment) or OWAS (Ovako Working Posture Analysis System) [7–9]. Through these tools, engineers can identify potential ergonomic risks and propose design improvements that enhance both worker well-being and production efficiency.

This study focuses on the creation of a digital human simulation in Tecnomatix Process Simulate Human, the application of RULA analysis to evaluate ergonomic risks, and the proposal of corrective actions to improve workplace ergonomics. The aim is to demonstrate how simulation-based ergonomic analysis can support data-driven decision-making in production system design.

Literature Review

Ergonomics, according to McCauley-Bush [1], integrates anatomical, physiological, and psychological principles into workplace design to ensure optimal human-system performance. Takala et al. [2] emphasized that poor ergonomic conditions are a leading cause of musculoskeletal disorders, which represent a major occupational health problem worldwide. Berlin and Adams [3] further noted that ergonomic design not only improves health outcomes but also enhances overall productivity and work satisfaction.

Simulation-based design enables the evaluation of workstations, tools, and workflows in a virtual environment prior to physical implementation. Tools such as Tecnomatix Process Simulate, CATIA Human, and Jack allow the designer to assess operator movements, reachability, visibility, and load distribution [4,5]. According to Marasová et al. [6], simulation helps to identify high-risk postures early in the design process, reducing the need for costly post-implementation modifications.

Digital human modeling (DHM) supports ergonomic evaluation through standardized assessment methods such as RULA, REBA (Rapid Entire Body Assessment), or OWAS [7]. Virtual ergonomics provides several key advantages over traditional evaluation methods. It enables the analysis of multiple work scenarios under controlled conditions, allows for iterative improvement, and facilitates communication between designers and operators [8,9]. Moreover, it supports the integration of ergonomic factors into the early phases of production system design, leading to better alignment between human capabilities and technological requirements.

As stated by Villani et al. [10], digital human simulations are essential for achieving sustainable and human-centered production, a key aspect of Industry 4.0. Combining DHM with motion capture or biomechanical data further enhances the accuracy of ergonomic analyses and supports continuous improvement in manufacturing systems.

Ergonomic Analysis

Ergonomic analysis and assessment of the work system are key tools for identifying and minimizing risks that may negatively affect employees’ health, safety, and productivity. The goal is to evaluate work tasks, postures, and movements in terms of physical load and to propose adjustments that support more efficient and safer work.

Various methods are used for this purpose, particularly RULA (Rapid Upper Limb Assessment), which evaluates body postures and determines the level of risk for musculoskeletal disorders. In the Siemens Tecnomatix Process Simulate Human environment, this method can be applied to a digital human model to simulate realistic work scenarios.

Digital ergonomic assessment allows the identification of high-risk movements already at the design stage, testing of different scenarios, and optimization of working conditions without the need for physical interventions. The result is a reduction of ergonomic risks, increased productivity, and overall improvement of the work environment.

As shown in Fig.1, the worker is depicted performing the evaluated work tasks, illustrating the postures and movements considered during the assessment.

Fig. 1 Worker performing the evaluated work tasks

Digital Human Modeling and Simulation

Ergonomic analysis and assessment were conducted using digital human modeling (DHM) within Siemens Tecnomatix Process Simulate Human. This approach allowed the creation of a digital human model representing the worker’s anthropometric characteristics and movement capabilities. The model was then used in simulations of actual work tasks, enabling the evaluation of postures, movements, and ergonomic risks, as well as the testing of potential workplace improvements before implementation.

The first work task involved handling components at a conveyor. Before ergonomic improvements, the RULA analysis yielded a score of 6, indicating high risk and the need for immediate intervention. The digital human model clearly illustrated the awkward postures, excessive bending, and extended reaching required by the worker (Fig.2).

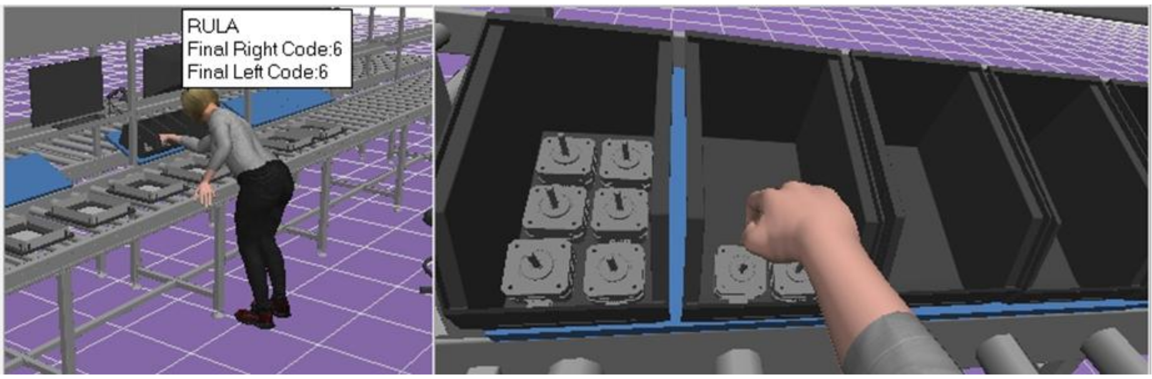

Fig. 2 Worker performing the first part of the assembly task

To improve ergonomics, an adjustable shelf was introduced, allowing components to be placed within easier reach. This modification reduced forward bending and stretching of the arms, resulting in a decreased RULA score of **4–5**, representing moderate risk and requiring only minor monitoring (Fig.3).

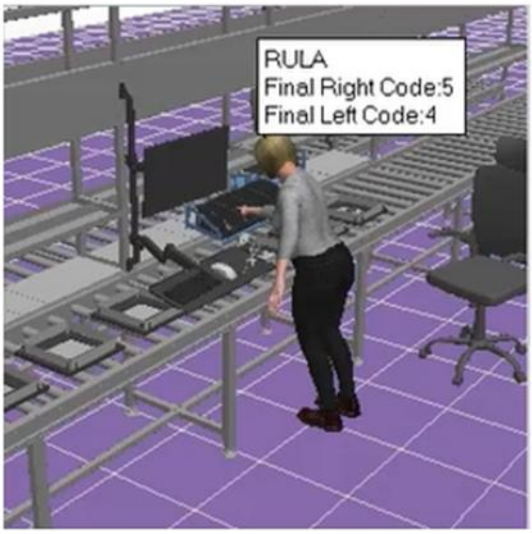

Fig. 3 Proposed ergonomic improvement for the first part of the task with an adjustable shelf

The second work task involved work at a computer workstation. Prior to modifications, the RULA score was **7**, indicating very high physical strain and the need for immediate intervention. The simulation showed excessive trunk bending, twisting, and awkward upper limb movements while using the monitor, keyboard, mouse, and barcode reader (Fig.4).

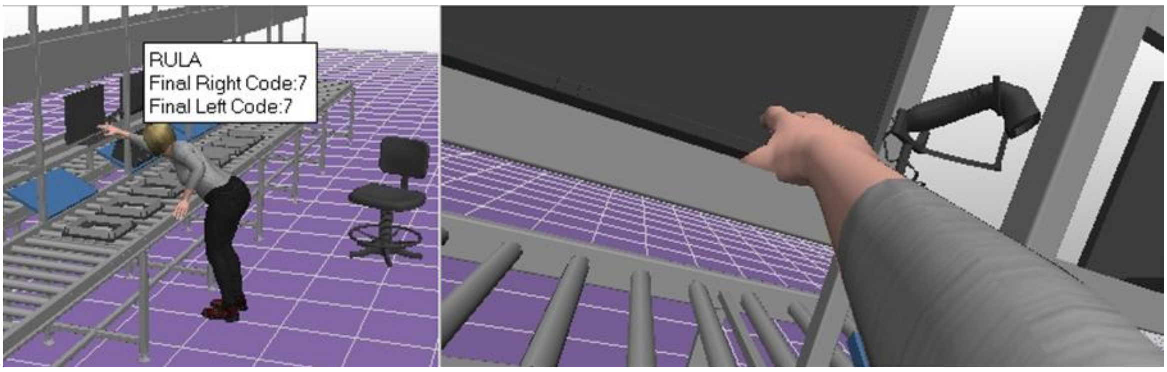

Fig. 4 Worker performing the second part of the assembly task

Ergonomic improvements included holders for the monitor, keyboard, mouse, and barcode reader, allowing optimal positioning within the worker’s line of sight and reach zone. These adjustments reduced static load and eliminated unnecessary movements, lowering the RULA score to **2–3**, which corresponds to acceptable ergonomic conditions (Fig.5).

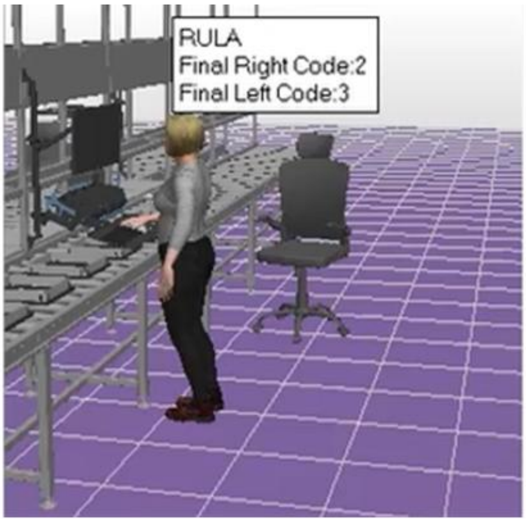

Fig. 5 Worker performing the computer-based task after ergonomic adjustments

The simulations demonstrated that even relatively simple ergonomic interventions, such as adjustable shelves or device holders, can significantly improve worker posture and reduce physical strain. The use of digital human modeling in combination with simulation allowed verification of proposed improvements before real-world implementation, reducing the risk of ineffective investments and enhancing workplace safety, comfort, and productivity.

Conclusion

The present study demonstrated the effectiveness of combining Digital Human Modeling (DHM) with simulation to assess and improve workplace ergonomics in a manufacturing environment. By applying RULA analysis to a digital human model, high-risk postures and movements were identified for two key work tasks: conveyor assembly and computer workstation operations.

The proposed ergonomic interventions, including an adjustable shelf for assembly components and holders for computer devices, led to significant reductions in RULA scores—from 6 to 4–5 for the conveyor task and from 7 to 2–3 for the computer task—indicating a substantial decrease in physical strain and risk of musculoskeletal disorders.

These results highlight that even relatively simple modifications can greatly enhance worker comfort, safety, and productivity. Furthermore, the use of DHM and simulations allows organizations to evaluate and validate ergonomic improvements before real-world implementation, minimizing costs and the risk of ineffective interventions.

Overall, the study confirms that simulation-based ergonomic assessment is a valuable tool for proactive workplace design, supporting healthier and more efficient work environments.

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A COMPARATIVE ANALYSIS FOR SELECTING VR DEVELOPMENT PLATFORMS IN MANUFACTURING

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Abstract: The adoption of Virtual Reality (VR) for creating digital twins and training simulations in manufacturing presents a significant challenge for researchers and engineers: selecting the appropriate software platform. This choice is critical, as it impacts the efficiency of converting complex Computer-Aided Design (CAD) data into performant, interactive experiences on standalone VR hardware. This paper provides a structured comparative analysis of three prominent software solutions — Unity, Unreal Engine, and the specialized Pixyz Review. We evaluate these platforms against criteria critical to industrial applications, including CAD data pre-processing capabilities, usability for non-experts, support for physics-based interactivity without extensive programming, performance optimization for standalone headsets, and licensing models. Our analysis positions Pixyz Review as a superior tool for the initial data preparation stage, while contrasting Unity's accessibility and performance with Unreal Engine's high-fidelity visuals and powerful visual scripting. The findings offer a foundational guide for academia and industry professionals new to VR, enabling them to make an informed decision based on their specific project requirements for iterative design and training processes.
Keywords: virtual reality; software comparison; unity; unreal engine; pixyz review

Introduction

The manufacturing industry is undergoing a profound transformation driven by digitalization, often encapsulated by the concept of Industry 4.0. Within this paradigm, Virtual Reality (VR) has emerged as a critical enabling technology, moving beyond entertainment to become a cornerstone for industrial innovation. Two applications, in particular, demonstrate significant potential for enhancing efficiency, safety, and design precision: digital twins and operator training. Digital twins provide a dynamic, virtual representation of a physical asset or system, enabling real-time monitoring, simulation, and analysis. Concurrently, VR-based training platforms offer a safe, immersive, and cost-effective environment for training operators on complex procedures, hazardous scenarios, and expensive machinery without risking real-world assets [1].

Currently, the market offers a range of software solutions, each with distinct strengths and weaknesses. This paper focuses on a comparative analysis of three prominent options:

1. **Unity:** A versatile and widely-used real-time development platform known for its relatively gentle learning curve and strong performance on mobile and standalone devices.
2. **Unreal Engine:** A powerhouse renowned for its cutting-edge graphical fidelity and a robust visual scripting system that minimizes the need for traditional coding.
3. **Pixyz Review:** A specialized software solution dedicated to the precise task of preparing, repairing, and optimizing high-resolution CAD data for real-time 3D experiences [1].

While previous studies have compared game engines in broad terms, there is a lack of focused research evaluating these platforms specifically through the lens of manufacturing needs, with particular emphasis on the critical CAD-to-VR pipeline, usability for non-programmers, and deployment on standalone VR hardware.

Therefore, this paper aims to provide a structured framework to address this gap. We present a theoretical comparative analysis of Unity, Unreal Engine, and Pixyz Review based on key criteria for industrial adoption:

1. effectiveness in CAD data handling and pre-processing,
2. usability and learning curve for beginners,
3. capabilities for creating necessary interactions like navigation and physics,
4. performance considerations for standalone VR headsets, and
5. overall cost of implementation.

The objective is not to crown a single "best" platform, but to provide a clear, evidence-based guide that enables researchers and engineers in manufacturing to select the most appropriate tool for their specific application in digital twins and operator training [2].

Methodology and Evaluation Criteria

This study employs a **structured qualitative framework** to compare Unity, Unreal Engine, and Pixyz Review based on key requirements for industrial VR applications. The analysis evaluates official documentation, feature sets, and industry best practices against five defined criteria:

1. **CAD Data Handling & Pre-processing** - evaluates capabilities for importing, repairing, and optimizing complex CAD assemblies for real-time use, with emphasis on workflow automation and iterative design support.
2. **Usability & Learning Curve -** assesses accessibility for manufacturing experts new to VR development, focusing on interface intuitiveness, documentation quality, and visual scripting tools to minimize coding requirements.
3. **Interactivity & Physics** - examines tools for implementing essential VR interactions (object manipulation, UI controls, basic physics) critical for training simulations and digital twin navigation.
4. **Standalone VR Performance** - analyzes optimization features for achieving stable performance on mobile VR headsets (e.g., Meta Quest), including built-in LOD, occlusion culling, and performance profiling.
5. **Licensing & Cost** - compares financial models (subscription, royalty, perpetual licensing) and total cost of ownership for academic and industrial adoption [3].

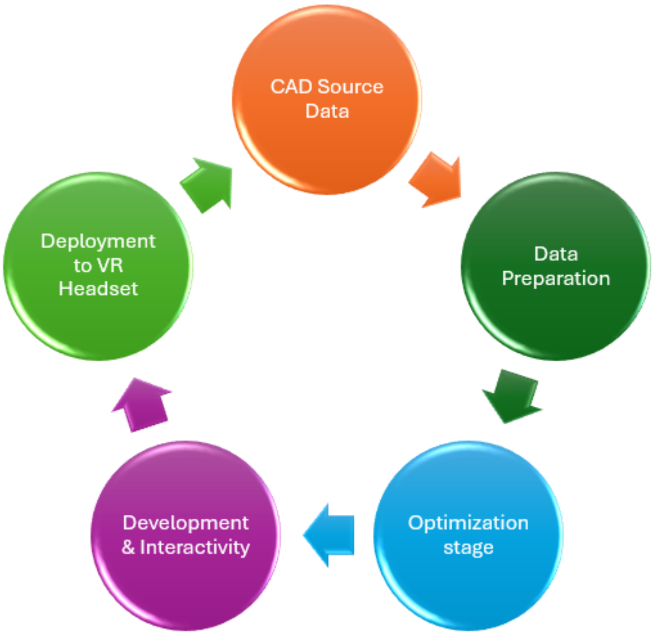

Fig. 12 The VR for Manufacturing Development Pipeline

Comparative Analysis

This section presents a direct comparison of Unity, Unreal Engine, and Pixyz Review based on the evaluation criteria defined in Chapter 2. The analysis is summarized in Table 1, followed by a detailed qualitative discussion of each platform's key strengths and weaknesses for manufacturing applications [4].

Tab. 7 Summary Comparison of VR Development Platforms for Manufacturing

Evaluation Criteria	Unity	Unreal Engine	Pixyz Review
CAD Data Handling	Poor native support	Good native support via Datasmith plugin	Exceptional. Core purpose is import, repair, and decimation of CAD data.
Usability & Learning Curve	Low to Moderate.	Steep initial curve	Low (for visualization). Simple UI for its core task of model preparation.
Interactivity & Physics	Strong. Robust, performant physics system	Very Strong. High-fidelity physics	Very Limited. Primarily for review, not building interactive experiences.
Standalone VR Performance	Excellent. Designed for performance across scales	Challenging. High-fidelity graphics are demanding	N/A (Is not a runtime engine)
Licensing & Cost	Per-seat subscription (Pro). Potential fees if revenue > $1M.	5% royalty on revenue over $1M. No upfront cost.	High upfront per-seat cost (perpetual or annual license).

Unity: The Accessible All-Rounder

Unity's greatest strength is its accessibility and strong performance on standalone VR hardware. Its ecosystem, including the Asset Store, offers plugins that can address its weak native CAD handling (e.g., using Pixyz for Unity). For teams needing to quickly prototype a training simulation for a Quest headset and who have some programming capacity (C# or visual scripting), Unity provides a flexible and performant foundation. However, building a seamless CAD-to-VR pipeline requires additional investment in third-party tools [5].

Fig. 13 Unity 3D Interface [5]

A. **The Toolbar** provides access to your Unity Account, Unity Cloud Services, and Unity Collaborate, the play, pause and step controls, and Unity Search, a layer visibility menu, and the Editor layout menu (which provides some alternate layouts for the Editor windows, and allows you to save your own custom layouts).
B. **The Hierarchy window** is a hierarchical text representation of every GameObject in the Scene. Each item in the Scene has an entry in the hierarchy, so the two windows are inherently linked. The hierarchy reveals the structure of how GameObjects attach to each other.
C. **The Game view** simulates what your final rendered game will look like through your Scene Cameras. When you click the Play button, the simulation begins.
D. **The Scene view** allows you to visually navigate and edit your Scene. The Scene view can show a 3D or 2D perspective, depending on the type of Project you are working on.
E. **Overlays** contain the basic tools for manipulating the Scene view and the GameObjects within it. You can also add custom Overlays to improve your workflow.
F. **The Inspector window** allows you to view and edit all the properties of the currently selected GameObject. Because different types of GameObjects have different sets of properties, the layout and contents of the Inspector window change each time you select a different GameObject.
G. **The Project window** displays your library of Assets that are available to use in your Project. When you import Assets into your Project, they appear here.
H. The status bar provides notifications about various Unity processes, and quick access to related tools and settings.

Unreal Engine: The High-Fidelity Powerhouse

Unreal Engine excels where visual realism is paramount. Its native Datasmith tool provides a strong pipeline for importing CAD data, and its Blueprints visual scripting system is arguably the most powerful available, allowing complex logic without writing code. This makes it ideal for high-end digital twin visualization. Its primary weakness is the performance overhead of its high-fidelity graphics, making it challenging to run complex scenes on standalone VR headsets without significant optimization expertise [6].

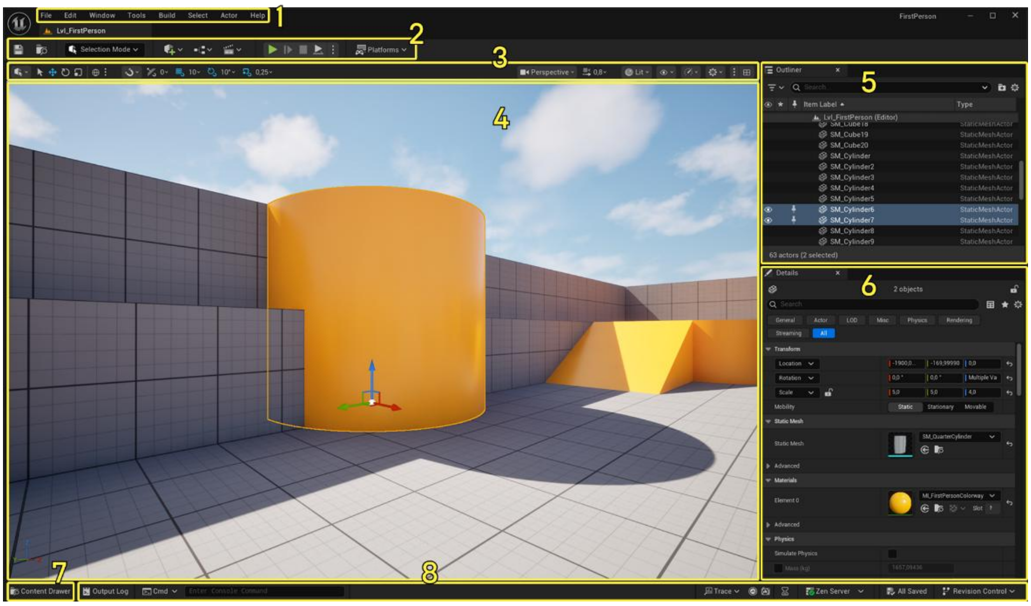

Fig. 14 Unreal Engine Interface [6]

1. **Menu Bar** uses these menus to access common application actions, like saving, and creating new levels. You’ll also find options for opening editor windows and tools that are useful for specific functions like debugging and more.
2. **Main Toolbar** contains shortcuts for some of the most common tools and editors in Unreal Engine, as well as shortcuts to enter Play mode (run your game inside Unreal Editor) and to deploy your project to other platforms.
3. **Viewport Toolbar** includes common tools used to manipulate objects in the level by moving, rotating, and scaling them, as well as snapping tools for moving objects along a grid, rotation angle, or scaling amount. It also includes perspective and orthographic views along with debugging and visualization view mode and other settings you can use while working in the viewport.
4. **Level Viewport** displays the contents of your Level, such as Cameras, Actors, Static Meshes, and so on.
5. **Outliner** displays a hierarchical tree view of all content in your Level.
6. **Details** panel appears when you select an Actor. Displays various properties for that Actor, such as its Transform (position in the Level), Static Mesh, Material, and physics settings. This panel displays different settings depending on what you select in the Level Viewport.

7. **Content Drawer** opens the Content Drawer, a temporary Content Browser window, from which you can access all of the Assets in your Project.
8. **Bottom Toolbar** contains shortcuts to the Command Console, Output Log, and Derived Data functionality. Also displays source control status.

Pixyz Review: The Specialized Data Preparator

Pixyz Review is not a direct competitor to the game engines but a specialized force multiplier. It is unparalleled in transforming large, complex CAD assemblies into optimized, VR-ready assets. Its standalone application is perfect for non-technical users (e.g., engineers) to perform design reviews in VR. However, it is not a development platform. For any interactivity beyond visualization, models must be exported to Unity or Unreal Engine, making it a critical first step in a pipeline rather than a standalone solution [7].

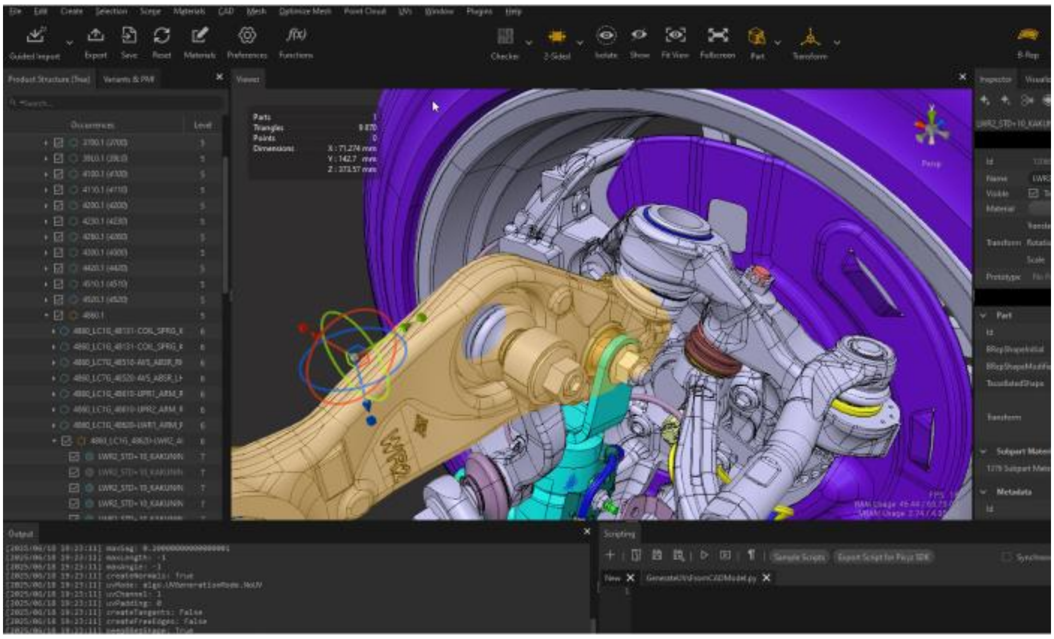

Fig. 15 Pixyz Review interface [7]

Framework for Selection

The comparative analysis in Section 3 reveals that there is no singular "best" software platform for developing VR applications in manufacturing. Instead, the choice is fundamentally dictated by the specific project requirements, team skills, and budgetary constraints. The findings demonstrate that Unity, Unreal Engine, and Pixyz Review occupy distinct and often complementary roles within the industrial VR development pipeline.

The core trade-off identified in this analysis is between **visual fidelity** and **performance accessibility**, with **data preparation** being a universal and critical first step. Unreal Engine pushes the boundary of graphical realism but demands greater technical expertise to achieve performance targets, especially on standalone hardware. Conversely, Unity prioritizes accessibility and performance across diverse hardware, making it a more pragmatic choice for scalable deployment. Pixyz Review addresses the universal bottleneck of CAD data preparation, a prerequisite for any serious industrial application regardless of the final engine chosen [8].

Selection Framework:

- **Choose Pixyz Review if:**
  - The primary need is for **rapid design review and validation** of CAD models in VR.
  - The project requires **exceptional data optimization** but has **no need for complex interactivity**.
  - It will be used as the **data preparation stage** for a pipeline in Unity or Unreal Engine.
- **Choose Unity if:**
  - The priority is **deployment on standalone VR headsets** (e.g., Meta Quest) and stable performance is critical.
  - The project requires a **strong foundation for physics-based interactions** (e.g., equipment disassembly).
  - The team values a **gentler learning curve** or has existing **C# expertise**.
  - The workflow involves **rapid prototyping** and iterative development.
- **Choose Unreal Engine if:**
  - **Maximum visual realism** and cinematic quality are the highest priorities (e.g., for marketing or high-end design review).
  - The team includes **technical artists** capable of harnessing its advanced graphics features.
  - The primary developers are **non-programmers** who can leverage the powerful **Blueprints visual scripting** system.
  - The application targets **PC-powered VR headsets** where hardware limitations are less constraining.

In practice, the most robust pipeline for a complex digital twin often involves a hybrid approach: using **Pixyz Review** for initial CAD data preparation and optimization, then importing the optimized assets into either **Unity** (for performance-focused training sims) or **Unreal Engine** (for high-fidelity visualization) [8].

Conclusion

This paper provided a structured comparison of three software platforms for creating VR applications in manufacturing. We have established that Unity, Unreal Engine, and Pixyz Review serve different, critical functions. Pixyz Review is the specialist for data preparation, Unreal Engine is the benchmark for visual fidelity, and Unity is the pragmatist for performance and accessibility.

The choice for researchers and engineers is not which tool is superior, but which tool is most appropriate for their specific goal. By aligning project requirements — whether for an immersive digital twin, a functional training simulator, or a streamlined design review process—with the strengths and weaknesses outlined in this analysis, teams can make an informed, strategic decision that maximizes efficiency, cost-effectiveness, and ultimately, the success of their VR implementation in an industrial context.

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MATERIAL HANDLING WITHIN THE WAREHOUSE USING A DRONE SYSTEM

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Abstract: The article focuses on exploring the possibilities of implementing robotic and automated systems in in-house logistics. Its primary objective is to analyse the impact of automation on the efficiency of logistics processes and to determine the key factors influencing the successful integration of modern technologies. Research findings, based on the analysis of current practices in industrial enterprises, demonstrate a significant positive effect of robotization on increasing productivity and reducing operational costs. Empirical evidence also reveals the limitations of traditional material handling methods, including low efficiency, high labour intensity, increased error rates, and unfavourable ergonomic conditions. Based on these identified shortcomings, a solution model is proposed that applies advanced automation tools to optimize material flow, enhance workplace safety, and lower costs. Furthermore, the study presents a methodological framework for the implementation of such systems and provides a comprehensive evaluation of their benefits for internal logistics.

Keywords: automation, robotic systems, material handling.

Introduction

The adoption of advanced technologies within intra-company logistics constitutes a critical vector of digital transformation, fully aligned with the paradigms of Industry 4.0. In response to mounting pressures for improved efficiency, agility, and cost containment, industrial enterprises are prioritizing the automation and robotization of their internal logistical workflows. Indeed, internal transportation systems emerge as essential for ensuring uninterrupted and streamlined material and information flows [1].

Contemporary innovations—encompassing robotic manipulators, automated guided vehicles (AGVs), autonomous mobile robots (AMRs), and drone-based systems—offer substantial potential for enhancing in-plant logistics (Industry 4.0 frameworks integrate cyber-physical systems, advanced robotics, and decentralized decision-making). Drones provide a novel modality for intra-enterprise transport, enabling rapid delivery of lightweight components, documentation, or samples. This approach substantially trims downtime, accelerates delivery cycles, and mitigates repetitive manual tasks [2].

The integration of UAV platforms with RFID, blockchain, and big data systems significantly enhances transparency and traceability in warehouse contexts. Fernandez-Carames et al. (2024) propose a modular UAV-blockchain architecture able to record inventory data with improved reliability and reduced latency, as demonstrated in industrial testbeds. Similarly, the fusion of drone-based scanning and RFID technologies accelerate inventory processes, yielding both operational efficiency and safety gains [3].

These advancements contribute to heightened operational responsiveness, improved worker safety, and enhanced competitive positioning in rapidly evolving industrial landscapes. The present study develops a methodological framework to guide the deployment of robotic and automated systems in internal logistics, thereby offering a rigorous assessment of their strategic value [4].

Technical conditions of implementation

Based on the analysis of the current state of intra-company transport, a concept for the implementation of autonomous drones was proposed as an alternative to the manual movement of materials and semi-finished products within the production facility. The initiative was partly prompted by the head of the technical support department, who during an internal meeting suggested utilizing the ceiling space of the production hall for collision-free movement of autonomous devices

Drone-based transport is therefore planned primarily for the most heavily utilized part of the operation – the main production room of approximately 400 m², where the majority of transfers between the warehouse, SMT placement line, quality control, and shipping take place daily. Implementing drones in this area will relieve employees from routine tasks while improving the reliability and smoothness of material flow.

- **Spatial and technical conditions for implementation**
- Production room dimensions: 20 m × 20 m
- Ceiling height: 5.5 m; usable flight height: 2.5 – 3.5 m above worker level, enabling safe parallel drone operation during production
- Number of workstations: 5 (Warehouse, SMT placement, Optical inspection, Intermediate storage, Shipping)
- Number of transport zones (landing points): 6
- Longest transport route: approximately 27 m
- Floor: flat industrial concrete – unsuitable for wheeled AGVs without suspension, highlighting the advantages of drone transport
- **Physical and digital infrastructure**
- Charging stations: 2 planned – near the warehouse and shipping area
- Network coverage: full 5 GHz Wi-Fi across the hall, LAN access point for the drone control unit
- Navigation and lighting: LED industrial lighting does not interfere with visual sensors or navigation systems
- Environmental conditions: stable temperature 20 – 24 °C, low dust, controlled humidity – ideal for sensitive electronics and safe drone flight
- **Characteristics of logistics flows**
- Daily production: approx. 3,000 PCBs
- Number of daily transport cycles: approx. 130 – 150
- Involved personnel: 4 operators working in two shifts
- Duration of a single transfer: 2 – 4 minutes
- Daily time spent on manual transport: approximately 7 – 8.5 hours

Key benefits of using drones in this space

- Optimization of material transport efficiency
- Minimization of physical strain and risk of product damage
- Safe utilization of vertical spaces
- Reduction of personnel-related costs
- More effective planning and monitoring of material flows

Table 1 Cost comparison: Drones vs. Employees

Parameter	Drone System	Manual Transport
Initial Investment Costs	€30,000	€0
Annual Operating Costs	€2,000	€52,800
Estimated Annual Cost Savings	approx. €50,800	–
Number of Daily Transports	150+	max. 130
Reliability	High	Variable (human factor)
Transport Speed	20 – 40 seconds	2 – 4 minutes
Risks	Technical malfunctions	Fatigue, errors, absenteeism
Safety	Predictable	Variable
Initial Investment Costs	€30,000	€0
Annual Operating Costs	€2,000	€52,800

Based on the presented data, it is evident that the current system is insufficient to efficiently meet the production requirements. Reliance on manual labor, time delays, disruptions, and the risk of component damage contribute to increased costs, reduced operational efficiency, and losses.

The implementation of drone-based transport offers the potential to:

- Significantly reduce costs (with potential annual savings of up to €50,000),
- Enable faster and more predictable material transfers,
- Enhance traceability and operational safety,
- Eliminate dependence on human resources at critical points.

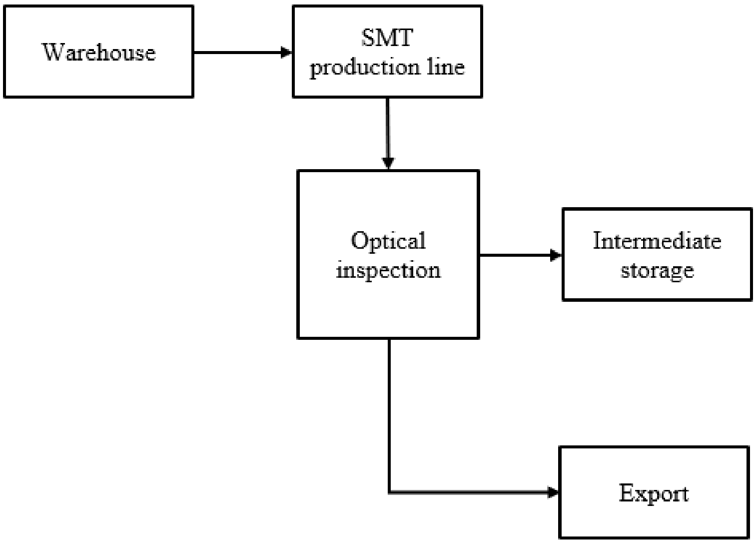

Fig. 1 Current floor plan of the operation [own processing]

Results and discussion

Based on the analysis of material flows within the ALFA s.r.o. production hall, the deployment of four autonomous industrial drones is proposed to ensure the regular transport of materials between five critical workstations: the warehouse, SMT placement line, optical inspection, intermediate storage, and shipping. The system is designed according to a rotational principle:

two drones operate actively, performing transport tasks, while the remaining two units are either charging or held as backup. This configuration ensures continuous coverage of the production logistics requirements, even in the event of a single unit failure or during scheduled maintenance.

Fig. 2 Example of an industrial drone [5]

Fig. 3 Example of an industrial drone [6]

- **Increased transport efficiency**

The deployment of drones facilitates substantially faster transport cycles—typically 1–2 minutes per segment—achieving time reductions of up to 50% compared with conventional manual handling methods.

- **Minimized physical strain and component damage**

Using drones equipped with stabilized holders for sensitive items, including those requiring electrostatic discharge (ESD) protection, reduces exposure to shocks and vibrations, thereby lowering the risk of mechanical damage.

- **Safe vertical separation**

By operating above ground-level activities, drones prevent interference with personnel and traditional transport vehicles, decreasing the likelihood of collisions within shared workspaces.

- **Reduced labor requirements**

A small fleet of 2–3 drones can decrease the need for human involvement in internal transport by 50–75%, potentially generating annual labor cost savings of €25,000–€35,000.

- **Enhanced material flow control and planning**

Digitally coordinated transport operations and real-time tracking increase the transparency of material movements, reduce errors, and facilitate prioritization based on production schedules or customer requirements.

Graphs showing efficiency before and after implementation

Figure 4 illustrates a comparison of selected operational metrics before and after the implementation of the drone system. The chart indicates a significant reduction in monthly operational costs, a decrease in average transport time, and an increase in the number of daily transport operations following the deployment of drones.

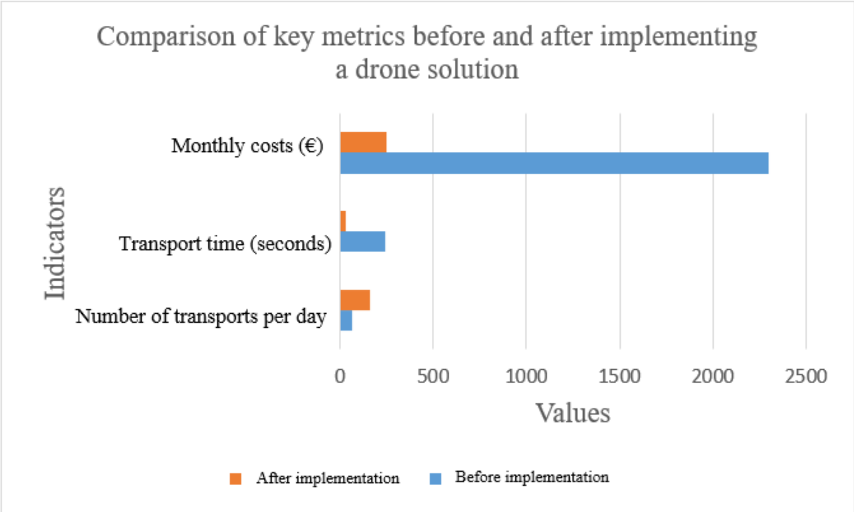

Fig. 4 Comparison of operational indicators before and after drone implementation [own processing]

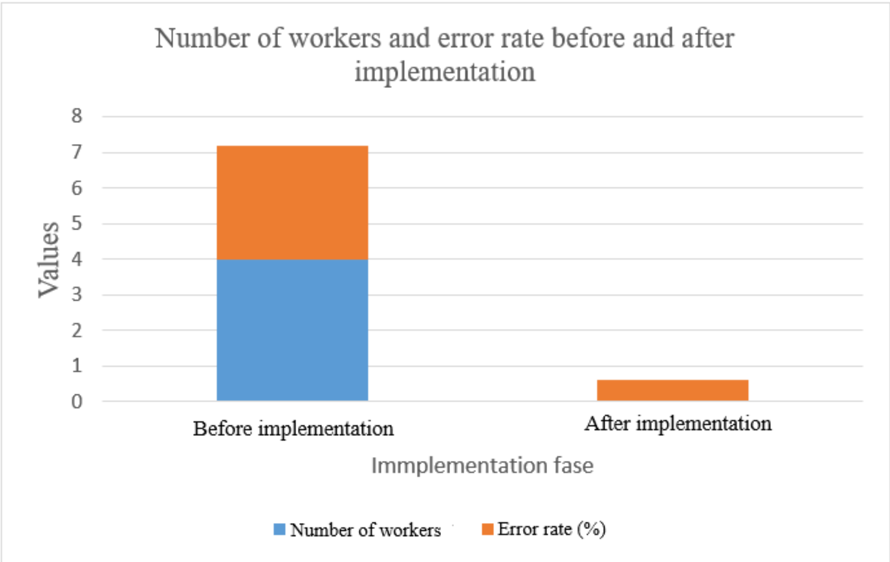

Fig. 5 Change in the number of workers and error rates in transportation before and after the implementation of drones [own processing]

Figure 5 illustrates the change in the number of personnel and error rate (%) in transport operations before and after the implementation of the drone system. The number of workers decreased, and the error rate dropped from approximately 3 % to below 1 %, indicating an increased reliability of the automated solution.

Conclusion

The analysis of intra-company transport at ALFA s.r.o. revealed that the manual system for moving materials and semi-finished products between workstations was characterized by time delays, reliance on personnel availability, risk of component damage, and limited traceability of material flows. The implementation of an autonomous drone system offers an effective solution to these challenges.

The proposed system comprises four industrial drones, optimized flight paths, charging stations, and safety measures adapted to the existing production hall. Simulations and operational models demonstrated substantial reductions in transport time, labor costs, error rates, and material damage, while improving the reliability and predictability of logistics operations.

Moreover, the study highlighted the potential for future expansion through additional automated systems, such as AGVs or collaborative robotic devices, enabling a phased modernization of internal logistics. Overall, the proposed approach supports digitalization, intelligent production management, and sustainable competitiveness, contributing to the implementation of Industry 4.0 principles.

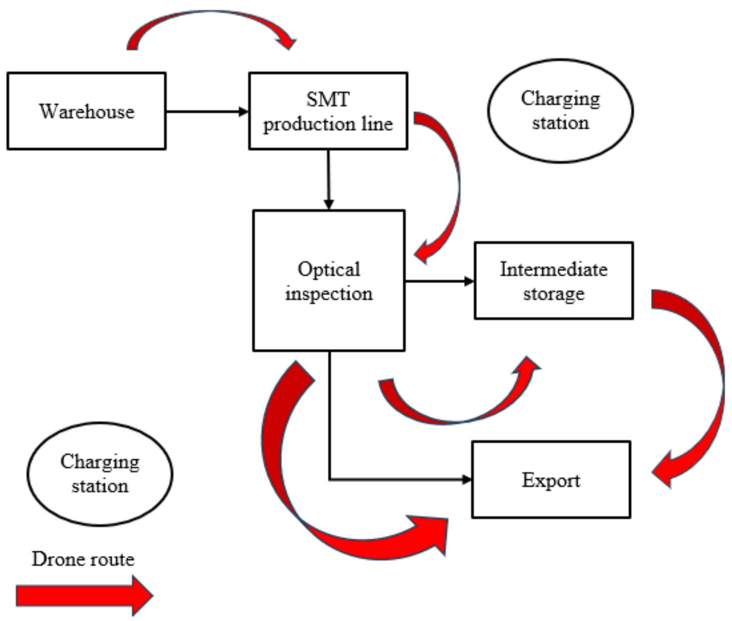

Fig. 6 Floor plan of the room after the implementation solution [own processing]

Acknowledgement

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CONTROL OF AN ARTICULATED ROBOT'S END-EFFECTOR USING THE DATA GLOVE

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Abstract: The paper presents the design and experimental verification of a virtual control system for an articulated robot's end-effector using the CyberGlove II data glove. The system maps finger bend sensors to the servo actuators of a 3D-printed gripper in real time. The solution combines CAD/CAM workflows (SolidWorks modelling), additive manufacturing of structural parts, and custom software (the C++ application "CyberGlove II RoboticHand") that links the glove to five servomotors, including weighting, motion ranges, and sensor calibration. The assembled prototype demonstrates synchronized transitions of the gripper from fully closed to fully open without noticeable latency and with high repeatability, confirming the suitability of the proposed architecture for precise manipulation tasks.

Keywords: Virtual reality, data glove, robotic device.

Introduction

Current developments in robotics and automation are opening up new possibilities across sectors, from industrial manufacturing to complex manipulation in hazardous or inaccessible environments. Among the key components of modern robotic systems are grippers that enable precise and efficient grasping and manipulation of objects. In recent years, increasing attention has been paid to integrating these mechanisms into applications that demand high precision and flexibility, as well as the ability to adapt to diverse tasks. The relevance of this topic stems from the growing demand for intelligent robotic systems capable of performing precise object manipulations in automated environments such as production lines and logistics centers. The topic addresses the integration of modern technologies such as 3D printing, servomotors, and data gloves into a single functional system that enables the execution of complex tasks with high precision.

Properties and Principles of Virtual Control

Virtual control is an advanced method of controlling industrial equipment and processes that uses digital technologies, simulations, and computer systems to improve operational efficiency and accuracy. It enables operators to remotely control and monitor machines or production processes through virtual environments or digital models. Virtual control is characterized by the integration of various technologies such as SCADA, PLC, and IoT which provide a coherent and flexible system for operating industrial machinery. A key feature of virtual control is real-time monitoring. In addition, simulation and modelling are often employed to test and optimize systems before physical implementation, thereby reducing costs and risks.

The principle of virtual control lies in the interaction between physical and virtual systems. Devices are equipped with sensors that collect real-time data such as temperature, pressure, and speed which are transmitted to the virtual control system. This system processes the data and provides operators with visualizations and control options for operating the machines. Based on the data, the virtual control system can perform operations such as process optimization, parameter adjustment, or corrective actions. By using simulations, virtual control systems can predict machine behaviour under various conditions, which supports decision-making and improves operational efficiency. This approach not only reduces operating costs but also increases flexibility and the ability to respond to changes in the system[1].

Importance of Virtual Tools in Industrial Automation

Virtual tools are transforming industrial automation by introducing innovative solutions in design, training, monitoring, and sustainability. They have become an integral part of modern industrial automation and significantly enhance the efficiency, flexibility, and accuracy of production and control processes. These tools span a wide range of technologies—from virtual reality (VR) and augmented reality (AR), through digital twins, to simulation software—all of which contribute to optimizing industrial operations [1]. One of the main advantages of virtual tools is the ability to carry out advanced simulation and testing before physical implementation. Engineers and designers can create digital models of machines, systems, or entire production lines, identify potential problems, and optimize performance without costly physical prototypes. Another key aspect is their role in remote monitoring and control. Thanks to the integration of Internet of Things (IoT) technologies, specialists can oversee and adjust production processes from anywhere in the world. This approach not only increases productivity but also enables rapid problem resolution and flexible adaptation to changing production requirements [2].

Use of Virtual Reality Hardware and Software

Data glove CyberGLove II

Data gloves are specialized technological devices that transfer human hand movement into a virtual environment. The CyberGlove II virtual glove model can be controlled in the CATIA V5 R15 CAD software. The glove contains sensors that capture the movements of the fingers and the entire hand, and software transmits this data to the computer. In this environment, 3D models can be manipulated and edited, and various constraints can be defined between them. The hand movements are displayed on the monitor and are used to control three-dimensional objects in virtual space. The glove can also capture more complex finger and hand gestures, making interaction with virtual objects feel almost like in the real world. When equipped with the CyberForce device, it is possible to simulate the weight of objects, further enhancing the impression of working with a real object.

Fig. 1 Data glove CyberGlove II [6]

Software Cyberhlove 2 RoboticHand

The **CyberGlove II RoboticHand** software was developed at the Department of Industrial and Digital Engineering. It was implemented in C++ and enables the CyberGlove II data glove to be linked to a servo-driven robotic device. Once the glove and the robotic device are connected, the weightings of the individual servomotors Fig. 2 are configured, and the range of motion is defined. Each of the five servomotors can be calibrated individually.

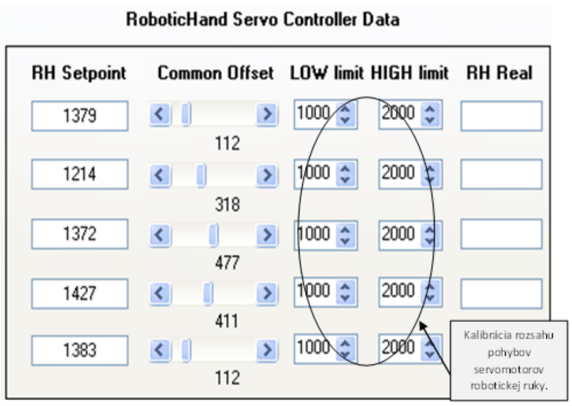

Fig. 2 Setting the range of motion of the servomotors [3]

Vybrané fyzické zariadenie pre ovládanie

An integral part of the experiment was to create a detailed and functional 3D model of the robotic device, whose components were designed to ensure reliable, functional operation. Each part performs a specific role within the assembly and, through its shape, dimensions, and placement, contributes to the overall stability and mobility of the system. The entire model was created in the SolidWorks CAD system.

Fig. 3 Complete model of the robotic device [4]

Another stage in implementing the robotic device was its physical fabrication using additive 3D-printing technology. This process took place in the laboratory of the Department of Industrial and Digital Engineering (KDaPI) at the Faculty of Mechanical Engineering, the Technical University of Kosice. The laboratory is equipped with modern systems for prototype development, design validation, and support for teaching in industrial automation and production digitalization. Its equipment includes 3D printers employing various technologies, CAD/CAM software solutions, scanning devices, and interactive workstations for working with smart technologies.

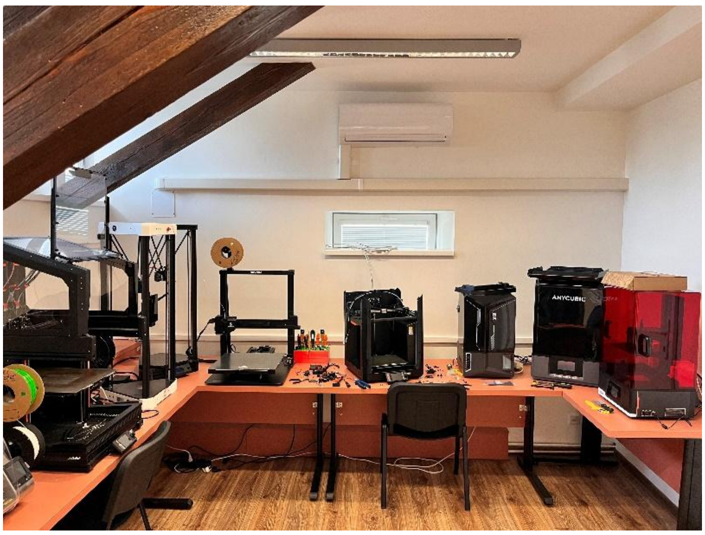

Fig. 4 Laboratory Additive Technologies Facility PK9/103.

After completing the assembly of the robotic device’s mechanical parts such as the base and moving arms the installation of the servomotors followed. These servomotors are crucial for motion control, as they enable precise, controllable rotation and movement of individual components, including the arms and gripper mechanisms.

Fig. 5 Installation of servomotors [4]

Synchronization of Movements Between the Data Glove and the Robotic Device

The process of controlling the robotic gripper was documented with a series of photographs that visually capture individual phases of the mechanism's motion, mirroring real human hand movements. This documentation serves as evidence of the implemented system's correct operation and its ability to faithfully reproduce human motion in real time. The images show the gripper transitioning from a fully closed to a fully open state. This motion range was achieved by sensing the hand with the CyberGlove II data glove, equipped with multiple sensors capable of capturing finger-joint flexion. The sensors convert the physical bending of the fingers into digital signals, which are then sent to the robotic device's control system.

The first photograph (Fig. 6) captures the moment when the fingers are maximally flexed inward, thereby generating a signal to fully close the gripper. The mechanism responded immediately and accurately, ensuring a secure grasp of the object or a simulated grasp.

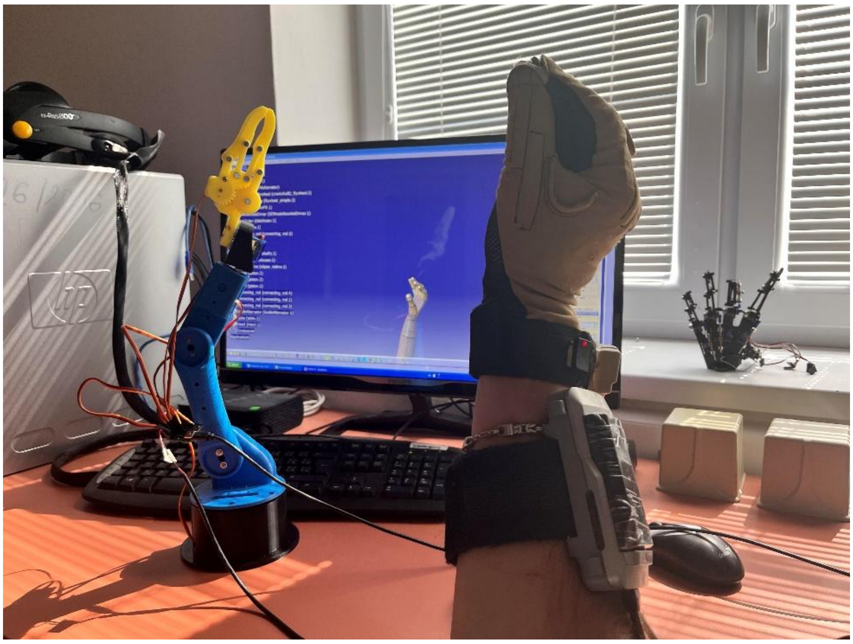

Fig. 6 Gripper in the closed position

In the second image (Fig. 7), a transitional state is captured. The fingers are only partially relaxed, causing the gripper to open to roughly half. This intermediate stage demonstrates the system’s ability to recognize and reproduce subtle motion variations, which is crucial when manipulating different types of objects.

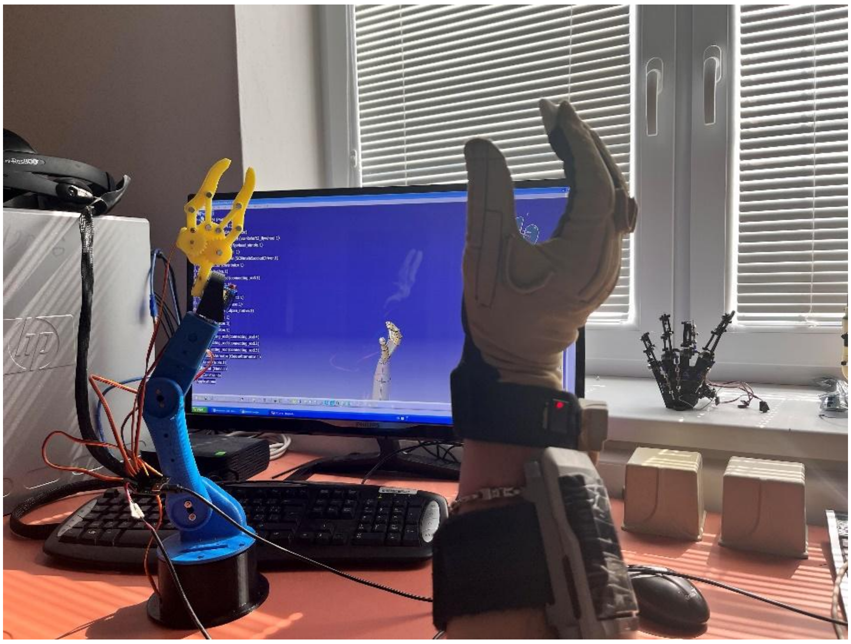

Fig. 7 Gripper slightly open

The third photograph (Fig. 8) depicts the gripper fully open, corresponding to the state when the palm is fully spread. The motion occurred without latency or jitter, confirming the quality of the sensor feedback and the correct operation of the control system.

Fig. 8 Gripper fully open

Successful synchronization of movements confirms the functionality of the entire proposed virtual control system.

Practical Applications of the System

Robotic devices have wide-ranging applications across many fields. They are most used in industry, where they serve to grasp and transfer parts or products. They assist with assembly, packaging, and sorting, thereby accelerating and simplifying production processes. They are also employed in logistics warehouses, where robots with grippers automatically handle goods. In research and medicine, they enable precise manipulation—for example in robot-assisted surgeries or when working with delicate samples. When combined with data-glove control, they can be deployed for teleoperation, in rehabilitation, or in developing assistive devices for people with reduced mobility. The robotic gripper described in this publication was designed and manufactured to demonstrate control using the CyberGlove II data glove. This technology provides intuitive control of robot motion based on natural human hand movements and offers potential applications in teleoperation, medical rehabilitation, and in environments that are hazardous or otherwise unsuitable for humans

.

Conclusion

The implemented system linking the CyberGlove II data glove with a 3D-printed robotic device has shown that virtual control can reliably transmit subtle human hand movements to servo actuators without noticeable latency. Calibration of the glove’s sensors and individual adjustment of the motion ranges for the five servomotors ensured high accuracy and repeatability of movements crucial for handling delicate or heterogeneous objects. Further development could focus on adding haptic feedback, for example via the CyberForce module, which would convey the force and weight of manipulated objects to the operator and enable active regulation of gripping force.

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FROM LAB TO FACTORY FLOOR: INDUSTRIAL ENGINEERING APPLICATIONS OF EDUCATIONAL ROBOTIC ARMS

Radko POPOVIČ - Milan FIĽO

Abstract: The integration of educational robotic arms into industrial engineering is transforming how businesses and universities approach Industry 4.0. Compact, affordable, and versatile, these systems enable simulation, prototyping, and workflow optimization through digital twin platforms. They provide a low-risk environment for testing automation strategies, validating kinematic and control models, and training the future workforce. Case studies demonstrate their role in reducing commissioning time, improving quality, and supporting small and medium enterprises with incremental automation. By bridging the gap between academic research and industrial deployment, educational robotic arms emerge as strategic enablers of smart, data-driven manufacturing.

Keywords: educational robots, modelling, production, simulation

Introduction

The fourth industrial revolution, commonly known as Industry 4.0, is reshaping how businesses design, operate, and optimize production lines. At the heart of this transformation lies the digital twin, a virtual replica of physical systems that enables simulation, monitoring, and optimization before real-world deployment. While industrial robots dominate large-scale automation, educational robotic arms are emerging as powerful tools for bridging the gap between academic research and industrial application. Compact, affordable, and versatile, these systems allow engineers, students, and businesses to experiment with automation strategies, validate digital twin models, and optimize workflows without the risks and costs of full-scale production trials.

Industrial Engineering Applications of Educational Robotic Arms

For businesses, the promise of Industry 4.0 is clear: greater efficiency, reduced downtime, and data-driven decision-making. Yet, implementing these technologies requires significant investment and carries operational risks. Educational robotic arms provide a low-cost, low-risk entry point for exploring automation concepts.

- Business need: Companies want to test automation strategies before committing capital.
- Solution: Educational robotic arms, integrated with digital twin platforms, allow simulation of production tasks such as pick-and-place, assembly, and inspection.
- Outcome: Firms can validate cycle times, identify bottlenecks, and optimize layouts virtually before scaling to industrial robots.

Fig. 1 Smart factory diagram with digital twin + robotic arm

A **digital twin** is more than a 3D model, it is a dynamic, data-driven representation of a system. In production lines, digital twins allow managers to simulate workflows, predict failures, and optimize throughput. Educational robotic arms are ideal for **digital twin prototyping** because they combine:

- **Affordability** for SMEs and universities.
- **Connectivity** with ROS, MATLAB, and Unity.
- **Repeatability** precise enough to validate motion strategies.

Case example: A university lab develops a digital twin of a robotic assembly station. Using educational robotic arms, students simulate part handling, test conveyor speeds, and measure cycle times. The validated model is then transferred to an industrial partner, reducing commissioning time and minimizing costly errors.

Fig. 2 CAD model vs. physical robotic arm executing same task

From a mechanical engineering perspective, educational robotic arms provide a **hands-on platform** for studying kinematics, dynamics, and control systems. Businesses benefit because these experiments translate into **better system design and optimization**.

- **Kinematic modeling:** Engineers can test forward and inverse kinematics in real time.
- **Control strategies:** PID tuning, trajectory planning, and motion smoothing can be validated.
- **Structural analysis:** The impact of stiffness, backlash, and payload on precision can be studied.

Fig. 3 Students analyzing robotic arm motion data

In industrial engineering, **workflow optimization** is a constant challenge. Production managers must balance throughput, quality, and cost. Educational robotic arms, when paired with digital twin models, allow businesses to:

- **Simulate production lines** with workstation layouts and robot-task assignments.
- **Identify bottlenecks** using simulation data.
- **Optimize cycle times** by experimenting with sequencing strategies.

Business case: A small electronics manufacturer uses educational robotic arms to simulate a PCB assembly line. By testing different robot placements and conveyor speeds in a digital twin, they reduce projected cycle time by 15% before investing in industrial robots.

Fig. 4 Miniature production line with robotic arms

One of the greatest challenges businesses face is the **skills gap**. As factories adopt smart technologies, workers must be trained in robotics, data analytics, and systems integration. Educational robotic arms are invaluable for workforce development because they:

- Provide **hands-on experience** with real robotic systems.
- Teach **programming, troubleshooting, and integration** skills.
- Familiarize workers with **digital twin workflows** and Industry 4.0 concepts.

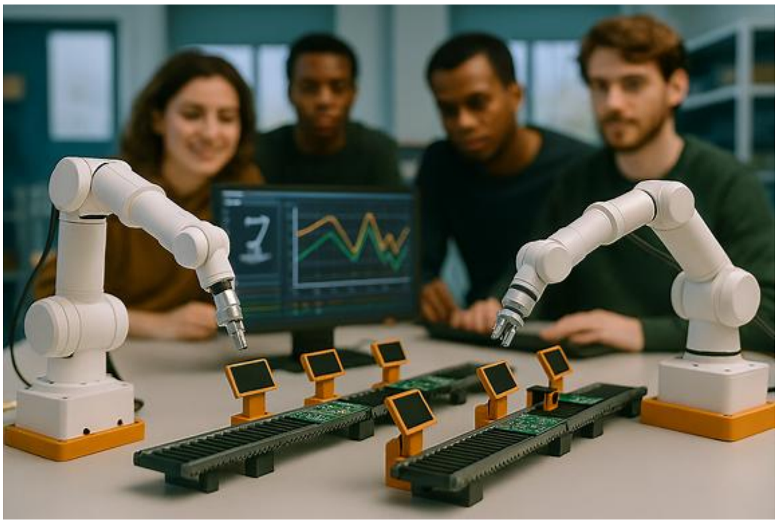

Fig. 5 Workforce training lab with robotic arms

The transition from lab experiments to factory deployment is where businesses see tangible returns. Educational robotic arms support this process by:

- **De-risking investments** through pilot projects.
- **Reducing commissioning time** with validated digital twin models.
- **Improving quality** by detecting errors early.
- **Supporting SMEs** with incremental automation.

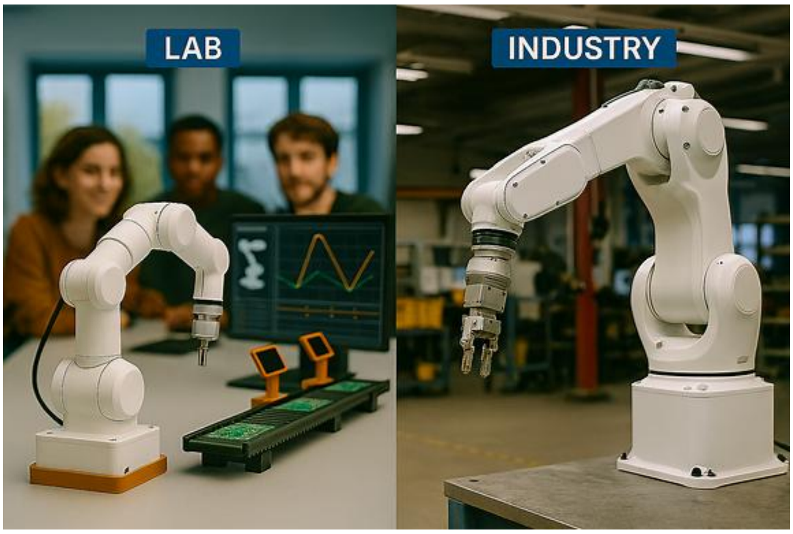

Fig. 6 Lab vs. industrial robot comparison

Conclusion

Educational robotic arms are redefining the relationship between education, research, and industry. By enabling digital twin projects, they allow businesses to simulate, test, and optimize production lines before committing to large-scale automation. For mechanical and industrial engineers, they provide a platform for modeling, control, and workflow optimization. For businesses, they reduce risk, accelerate deployment, and prepare the workforce for Industry 4.0. In short, these compact systems are more than academic curiosities—they are strategic enablers of smart manufacturing, ensuring that the journey from lab to factory floor is efficient, data-driven, and future-ready.

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VIRTUAL AND HAPTIC GLOVES: TECHNOLOGY COMPARISON AND PRACTICAL APPLICATIONS

Matúš LEŠČINSKÝ – Juraj KOVÁČ - Erik VARJÚ

Abstract: The presented publication provides a comprehensive overview of haptic gloves and highlights the latest advances in hand motion sensing technologies. It describes devices such as CyberGlove, Manus VR, and HaptX Gloves, examining their functional capabilities, underlying technologies, and price ranges. The analysis aims to guide professionals and researchers in selecting suitable haptic solutions for applications in virtual reality, robotics, medical training, and teleoperations.

Keywords: haptic gloves, haptic technologies, virtual reality (VR), augmented reality (AR), motion capture

Introduction

The evolution of human-computer interaction is reshaping how people design, learn, and collaborate in virtual and hybrid environments. Rapid advances in virtual, augmented, and mixed reality as well as telerobotics have created a demand for interfaces that reproduce the richness of human touch. Traditional controllers and optical tracking systems, while adequate for visual immersion, cannot convey the subtle kinesthetic and tactile cues of natural hand movements.

Haptic gloves have therefore become a key technology. By combining precise motion capture with force and tactile feedback, they allow users not only to visualize but also to *feel* virtual objects. Their applications range from industrial assembly and remote robot manipulation to medical training, immersive education, gaming, and rehabilitation, illustrating their strategic role in the emerging “internet of skills,” where manual expertise can be digitized and reproduced at a distance.

Recent progress in lightweight mechanical design, actuation principles, wireless communication, and software integration has turned early prototypes into commercially viable products. At the same time, a rapidly expanding market calls for clear, evidence-based comparisons of available solutions.

This article responds to that need by presenting a technology-oriented review of leading haptic gloves CyberGlove III, Manus Prime X, HaptX G1, SenseGlove Nova 2, and Dexmo Enterprise Edition. It examines their motion-tracking precision, feedback mechanisms, ergonomic properties, and price structures, offering guidance for researchers and industry professionals and pointing to trends likely to shape the next generation of haptic interfaces.

Data Gloves Comparison: Technologies, Parameters, and Price Analysis

1. CyberGlove Systems: From Pioneer to Modern Standard

CyberGlove Systems is a pioneer in the field of data gloves, with its history dating back to the late 1990s. The evolution of its product line shows a gradual shift towards higher accuracy, comfort, and modularity. The first generation (CyberGlove I) of this technology laid the foundational stone. It was a pioneering device that demonstrated the viability and enormous potential of hand motion capture for digital applications. It is no longer manufactured, and its specifications are now considered obsolete.

CyberGlove II: The second generation represented a significant improvement over its predecessor. It featured enhanced tracking accuracy, ergonomics, and overall reliability. For a long time, the CyberGlove II held the status of the "industry standard" in hand motion capture and is still in use in many labs and studios today [1]. The CyberGlove II, developed by Immersion Corporation, is equipped with 18 motion sensors and communicates with a computer via Bluetooth technology. The data glove provides highly accurate angular measurement and enables the transformation of hand and finger movements into digital data in real time. Its more detailed technical specifications are as follows: 18 motion sensors, sensor deviation of <1 degree, wireless technology: 2.4GHz, battery life: 3 hours, interface: USB port for the wireless receiver. [2]

CyberGlove III: The third and current generation represents the most modern and technologically advanced model in the company's portfolio. Compared to previous generations, it offers several key improvements:

- Motion Tracking: Tracks the bend of each joint, thumb opposition, grasp aperture, and wrist flexion.
- High Accuracy: Provides high-resolution data (up to 0.1°).
- Sampling Rate: Up to 120 Hz.
- Calibration: Simple software calibration.

Parameters of the CyberGlove III:

- Number of Sensors: 18 or 22 (including wrist)
- Resolution: < 0.1°
- Sampling Rate: 100-120 Hz
- Interface: USB
- Compatibility: Windows, Linux

While the CyberGlove I and II were important milestones, the CyberGlove III is the culmination of this evolution. It is the direct successor and surpasses its predecessors in all parameters, making it one of the most accurate and reliable commercially available hand motion tracking solutions in the world.

Price: From ~ €13,000 (base model). The price increases with add-on modules for motion tracking and feedback [3].

Fig. 1. CyberGlove I / II (left image) & CyberGlove III (right image) [4]

2. Manus Prime X Haptic Gloves: The Flagship Wireless VR Gloves

The Manus Prime X Haptic VR gloves were designed to deliver one of the most immersive and precise virtual reality experiences available. Each glove combines advanced 9-DoF sensors and flex sensors to track finger movements with exceptional accuracy, while integrated vibrotactile motors provide individual haptic feedback for every finger. This allows users not only to see but also to feel digital interactions, making the gloves highly effective for professional VR training, research, and design applications.

The gloves were built for flexibility and comfort, featuring a washable textile base in multiple sizes, a quick 3-gesture calibration system, and a swappable battery that provides up to five hours of continuous use. Through the Universal Mounting System, they can be paired with tracking devices such as HTC Vive, Manus Pro, or Tundra trackers. Integration with platforms like Unity, Unreal Engine, IC.IDO, VRED, and Siemens Teamcenter is supported through the Manus Core SDK, enabling seamless use in enterprise and creative workflows.

While praised for their precision tracking and per finger haptics, the Prime X Haptic VR gloves have since reached End of Life (EOL) status and are no longer being manufactured. At the time of availability, they retailed for around 4,700€ , depending on the package and licensing options. Despite their discontinuation, they remain an important milestone in the evolution of VR input technology, bridging the gap between physical and digital interaction [5].

Feature	Prime X Haptic VR Gloves
Finger Tracking	9-DoF IMU + flex sensors (2-joint)
Haptic Feedback	Per-finger vibrotactile motors
Battery Life	~5 hours (swappable)
Integrations	Unity, Unreal, IC.IDO, VRED, Siemens Teamcenter, SDKs
Mounting Options	Vive, Manus Pro, Tundra trackers
Calibration	3-gesture, stored profile
Size Options	Washable textile; S/M and M/L [6].

Fig. 2. Manus Prime X Haptic Glove [7]

3. HaptX Gloves G1

HaptX Gloves G1 are advanced haptic gloves designed for professional and enterprise use.

They use 135 microfluidic actuators that physically press against the skin of the fingers (about 0.9 mm displacement) and palm (about 1.5 mm), creating a realistic sense of touch. The gloves also provide force feedback of up to 8 lb (about 3.6 kg) per finger and up to 40 lb (about 18 kg) per hand, with a response time of around 23 ms.

Each glove tracks 36 degrees of freedom with very high positional accuracy of about 0.3 mm and almost no latency. They work with an external Airpack, a wireless compressed-air unit that weighs about 8.8 kg, has a battery life of 2-3 hours, operates quietly (about 55 dB), and connects via Wi-Fi with a range of about 30 meters.

The system includes an SDK with plugins for Unity and Unreal Engine, a C++ API, and integration with ROS for robotics. It also supports multi-user collaboration and vibrotactile feedback for simulating surface textures. Gloves are available in sizes S, M, L, and XL, with each glove weighing about 0.45 kg.

Prices (September 2025):

- A single pair in one size costs about 4,716 €.
- A bundle including all four sizes (S, M, L, XL) costs about 3,862 € per pair.
- A monthly subscription of about 425 € is required, which includes the Airpack, SDK, service, and support.

HaptX Gloves G1 provide realistic touch through microfluidic and force feedback technology, precise motion tracking, and advanced software integration, making them one of the most sophisticated haptic glove systems available [8].

Fig. 3. Haptx Gloves G1 [9]

4. SenseGlove Nova 2

The most advanced glove from SenseGlove right now is the SenseGlove Nova 2, released in 2024. Nova 2 introduces a new active contact feedback system with a pressure strip in the palm, making it possible to feel holding or pressing against virtual objects. Each of the four main fingers (thumb, index, middle, ring) has a magnetic brake that can deliver up to 20 Newtons of resistance per finger (quality control maximum up to 24 N). This allows the glove to simulate the weight and hardness of objects very realistically.

In addition, it has vibrotactile feedback through linear resonant actuators (LRA) located in the palm, thumb, and index finger. This allows the glove to reproduce sensations like clicks, taps, or vibrations.

Finger tracking is handled with flexible sensors: four flexion sensors and one abduction/adduction sensor for the thumb, giving six degrees of freedom in total. This provides accurate motion capture of the hand.

The built-in lithium-ion battery has a capacity of about 3,450 mAh, lasting for around three hours of continuous use. Communication is wireless over 2.4 GHz, with a refresh rate between 60 and 90 Hz. One glove weighs about 350 grams.

Nova 2 is compatible with Windows, Linux, and Android systems. It uses SenseCom software for integration and works with external tracking devices such as Meta Quest or HTC Vive controllers.

The official price is around €5,999 excluding VAT.

Nova 2 combines active contact feedback, strong force resistance, vibrotactile sensations, precise finger tracking, and wireless usability. This makes it the flagship product from SenseGlove for professional VR training, simulation, and research [10].

Fig. 4 SenseGlove Nova 2 [11]

5. Dexmo Gloves

Dexta Robotics currently offers its most advanced model called the Dexmo Enterprise Edition. It is a wireless force-feedback exoskeleton glove built for enterprise training, research, and VR applications. The glove combines motion capture with kinesthetic feedback so users can both see and feel virtual objects.

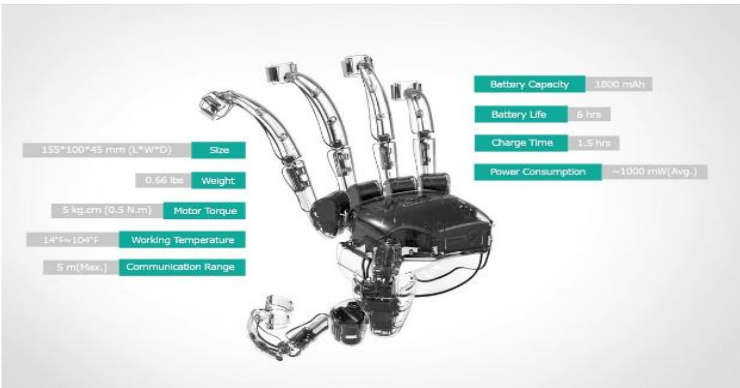

Fig. 5 Dexmo gloves specifications [12]

It captures full hand movement with 11 degrees of freedom: three for the thumb (rotation, split, bending) and two for each of the other four fingers. The glove provides variable force feedback, which means you can feel resistance and stiffness for example, the difference between holding a stone or a rubber ball, pressing a button, or cracking an egg. Safety is ensured through torque monitoring and capped output; each finger module can generate about 0.3 N·m of torque, which is below the average maximum torque of a human finger.

Dexmo runs wirelessly over a 2.4 GHz connection, with latency between 20 and 50 ms and a range of up to 5 meters. One glove weighs about 320 g and is powered by a 2000 mAh Li-Po battery, which lasts up to 6 hours and recharges in about 1.5 hours. The system comes as a development kit including two gloves, dongles, adapters, and an SDK (LibDexmo and Unity plugin) that supports headsets such as Oculus, HTC Vive, PSVR, and HoloLens.

The company does not publish the price officially. According to one community report, the price was around €12,000 per glove, which suggests it is mainly intended for enterprise and research use [13].

Fig. 6 Dexmo glove review [14]

Conclusion

The target of this contribution was to provide an analytical overview of advanced haptic gloves available on the market, focusing on their technologies, functional parameters, and price positioning. The method applied was a comparative analysis of selected leading models: CyberGlove III, Manus Prime X, HaptX G1, SenseGlove Nova 2, and Dexmo Enterprise Edition based on technical documentation, published studies, and vendor sources.

The goal was to highlight the technological diversity of these devices and to illustrate how different manufacturers approach the challenges of force feedback, vibrotactile stimulation, finger tracking, and ergonomic design. The outcomes show that each glove emphasizes different strengths: from high-accuracy motion capture (CyberGlove III) to strong force feedback (Dexmo), advanced microfluidic actuators (HaptX), or practical wireless usability (SenseGlove Nova 2). Prices vary significantly, ranging from several thousand euros to more than ten thousand euros per unit, which directly affects their adoption in research, training, and industrial applications.

It is assumed that the analyzed group of five to six devices cannot cover the entire spectrum of available solutions. The market also includes other important manufacturers such as Teslasuit, VRgluv, MoCap Pro Gloves, CaptoGlove, and Hi5 VR Gloves, which were not included here due to space limitations. Nevertheless, the presented comparison provides a representative sample of current state of the art technologies and supports professionals in selecting suitable haptic gloves for specific use cases.

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LABORATORY ENVIRONMENT FOR MODERN EDUCATION - LINKING EDUCATIONAL ROBOTICS AND INTERACTIVITY

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Abstract: One of the most effective responses to the challenge of digitalisation in the education process has been the creation of laboratory environments for modern education. These environments serve as bridges between academic theory and practical industry applications. Unlike traditional classrooms, laboratories enable active experimentation, problem-solving, and collaboration. When equipped with educational robotics platforms, these laboratories foster interactive learning experiences where students can directly engage with technologies similar to those used in manufacturing and automation. The introduction of educational robots, such as Wlkata Mirobot, represents a breakthrough in making advanced robotics accessible, affordable, and pedagogically effective for students at different levels of education
Keywords: laboratory, education, mirobot, wlkata

Introduction

The digital transformation of industry, summarised under Industry 4.0, has changed the skills required from engineering graduates. Modern manufacturing environments are increasingly automated, data-driven, and robotised, demanding both theoretical knowledge and practical competencies. Traditional teaching methods often fail to prepare students for these challenges. Laboratory environments equipped with educational robotics provide an effective solution by offering interactive, hands-on experiences. Robots such as Wlkata allow students to engage directly with automation technologies, fostering active learning, creativity, and problem-solving. When combined with modelling, simulation, and digital twin technologies, these laboratories enable students to experiment, optimise, and analyse processes in both virtual and physical environments. This article explores how integrating Wlkata robots with interactive laboratory setups supports modern engineering education. It emphasises the benefits of hands-on experimentation, simulation, and digital twins for understanding complex industrial workflows and developing the skills necessary for Industry 4.0.

Challenges and areas for improvement the education in laboratory

Educational robotics has evolved from simple kits like LEGO Mindstorms to advanced platforms such as Dobot Magician, KUKA Education, and Wlkata. LEGO fosters creativity and logical thinking but offers limited industrial relevance. Dobot provides multifunctional capabilities (pick-and-place, 3D printing), while KUKA delivers professional-grade robotics training at higher cost. Wlkata bridges this gap, balancing affordability, usability, and industrial realism.

Despite the progress, several challenges remain in the adoption of educational robotics and laboratory-based teaching. High initial costs of hardware, lack of standardized communication protocols, and the need for continuous updates are recurring themes in the literature. Furthermore, the rapid pace of technological change often outstrips the ability of educational institutions to adapt curricula accordingly. Another challenge is the human factor. Even as automation and artificial intelligence advance, the literature stresses the importance of human

oversight, decision-making, and ethical responsibility. Educational laboratories must therefore not only equip students with technical knowledge but also cultivate their ability to critically interpret data and make informed judgments.
Modelling and simulation are critical in modern education, enabling students to experiment with complex scenarios safely. Digital twins extend this by offering real-time virtual replicas of physical systems, supporting process optimization, predictive analysis, and workflow testing. Integrating robotics, simulation, and digital twins in laboratory environments enhances comprehension, engagement, and practical skill development.

Tab. 8 Technologies as initiative to a change

Rank	Robot	Suitability for Higher Education
Wlkata Mirobot	★★★★★	Best price/performance ratio. Sufficiently realistic (6-DOF), supports simulation and digital twin integration, affordable for larger student groups. Suitable for introductory courses in robotics, automation, and modeling.
Dobot Magician	★★★★☆	Multifunctional (robotics, 3D printing, pick-and-place), more affordable than industrial robots. Ideal for project-based courses, but limited industrial relevance (lower accuracy, 4 axes).
ABB IRB 120 (EduPack)	★★★★☆	High industrial relevance and strong RobotStudio software for simulation and digital twins. Excellent for advanced courses, but high cost limits wider deployment.
KUKA Education Robot	★★★★☆	Industrially realistic solution with strong PLC integration and high precision. Suitable for master’s and PhD programs. High costs and more complex onboarding required.
Universal Robots UR3e (Edu)	★★★★☆	Excellent for Industry 4.0 and collaborative scenarios. High cost limits the number of units in teaching, but very suitable for specialized laboratories.
Franka Emika Panda	★★★☆	Excellent for research (AI, adaptive control, ROS). Less versatile for general university labs, but highly beneficial for specialized courses.
LEGO Mindstorms	★★☆☆☆	More appropriate for secondary education. Good for teaching programming basics and teamwork, but very limited industrial relevance for higher education.

Laboratory environments, especially project-based setups like Lean Learning Factories, promote active learning, teamwork, and problem-solving. Despite high initial costs and technical integration challenges, studies confirm that interactive robotics education develops both technical and soft skills, preparing students for Industry 4.0.
Key insights:

- LEGO Mindstorms – best for early education, creativity, STEM basics, not industrially relevant.
- Wlkata Mirobot – cost-effective, compact, and suitable for entry-level robotics in universities, bridges simulation and real-world control.
- Dobot Magician – versatile educational tool with multifunctional capabilities, ideal for project-based learning.
- Industrial-grade robots (KUKA, ABB, UR, Franka) – expensive but provide the highest industrial relevance, full PLC integration, and strong support for digital twin and Industry 4.0.

Mirobot in laboratory conditions at KPaDI

The laboratory has been developing for 2 years with the support of research projects carried out at KPaDI as an integrated platform for the design, modelling and simulation of production and logistics flows and digitalisation in the context of Industry 4.0. The Learning Factory at KPaDI allows students to enrich their practical skills and competencies related to modern methods, techniques and tools using educational robots Wlkata, which also have their own platform for the creation and testing of digital twins.

Fig. 1 Laboratory equipment Wlkata Mirobot at KPaDI

The research was conducted in a purpose-built laboratory environment designed to emulate industrial production settings. The laboratory, modelled after a Lean Learning Factory concept, integrates physical robotic workstations, simulation software, and digital twin platforms. Key components include:

- Wlkata educational robots: Compact, programmable robotic arms capable of performing pick-and-place operations, trajectory planning, and collaborative tasks. These robots support both visual programming interfaces for beginners and advanced coding (Python, C++) for experienced users.
- Simulation tools: Software platforms for virtual experimentation, allowing students to test robotic operations, optimise workflows, and predict outcomes without risking hardware damage.
- Digital twin models: Virtual replicas of physical workstations, enabling real-time monitoring, control validation, and scenario testing in a virtual environment.
- Interactive interfaces: Tablets, PCs, and VR/AR devices enabling students to control robots, visualise simulations, and interact with digital twins.

The laboratory was arranged to promote collaborative learning, with teams of 3–4 students assigned to each workstation. Each team had access to physical robots, simulation software, and digital twin interfaces to encourage a blended learning approach.

Conclusion

This study highlights the value of laboratory environments integrating educational robotics, interactivity, modelling, simulation, and digital twin technologies in modern engineering education. In summary, the study demonstrates that:

- Wlkata robots provide a cost-effective and industrially relevant platform for interactive learning.
- Laboratory-based projects combining robotics, simulation, and digital twins enhance student engagement, technical competence, and problem-solving abilities.
- Interactivity and hands-on experimentation are key drivers of motivation and knowledge retention.
- Simulation and digital twin technologies complement physical robotics, enabling safe, scalable, and immersive learning experiences.
- Challenges remain in scaling, technical integration, and initial student onboarding, but the overall educational benefits outweigh these limitations.

Laboratory environments integrating educational robotics, interactivity, simulation, and digital twin technologies provide an effective platform for modern engineering education. Wlkata robots offered accessible, industrially relevant hands-on experiences, while simulations and digital twins reinforced conceptual understanding and allowed safe experimentation. Students developed technical skills, analytical thinking, collaboration, and decision-making competencies. Interactivity and project-based tasks increased motivation and knowledge retention. Despite challenges related to onboarding, technical integration, and resource limitations, the approach proved highly effective in preparing students for Industry 4.0. Future research should explore scalability, long-term learning impacts, and integration with emerging technologies such as augm ented reality, AI, and cloud-based simulation platforms, further enhancing laboratory-based interactive education.

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INNOVATIVE APPROACHES IN TEACHING 3D METROLOGY

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Abstract: Metrology as an interdisciplinary science is a key pillar of modern industry, combining elements of physics, mathematics, computer science, mechanical engineering, and electrical engineering. This article focuses on innovative methods of teaching 3D metrology with the aim of increasing student interest in this field. We introduce modern methods and technologies such as coordinate measuring machines and optical scanners, and integrate elements of artificial intelligence (AI), virtual reality (VR), and augmented reality (AR). We also present the use of industrial robots and their programming through the Visual Components software platform. The aim is to show how these innovations can transform traditional teaching into an interactive and practical form, thereby increasing student motivation and their readiness for industrial practice. The article is based on theoretical knowledge and practical examples, with an emphasis on the interdisciplinary nature of metrology.

Keywords: 3D metrology, innovative teaching, artificial intelligence, virtual reality, robotics, Visual Components.

Introduction

Metrology, the science of measurement, is one of the most interesting and interdisciplinary fields in today's scientific and technical world. Its roots go back to ancient times, when measurement was used to build pyramids and for navigation, but today it's expanding into the digital age, where it includes precise measurements on a nanoscale up to large industrial components. As an interdisciplinary science, it combines physics (optics, mechanics, quantum physics), mathematics (geometry, statistics), computer science (data processing algorithms), and technical sciences (mechanical engineering, electrical engineering, materials science). In the context of 3D metrology, this involves three-dimensional measurement of shapes, surfaces, and dimensions of objects, which is essential in the automotive industry, aviation, medicine, and manufacturing processes.
Nowadays, when students face a multitude of stimuli from the digital world, it is a challenge to increase their interest in metrology. Traditional teaching methods, based on theoretical lectures and static exercises, often fail to capture the dynamics of this science. Innovative approaches that integrate modern technologies can address this problem. This article focuses on ways to use 3D metrology in combination with AI, VR/AR, and robotics to make teaching more attractive and practical. The goal is not only to increase student interest, but also to prepare them for the real challenges of Industry 4.0. [1, 2]

Increasing students' interest in metrology

Metrology often suffers from the stereotype of being a "dry" and mathematically demanding discipline. However, its interdisciplinary nature offers opportunities for creative applications. Students can see how metrology contributes to the development of autonomous cars (sensor measurements), medical implants (precise bone scanning), or even art (digitization of sculptures). To increase interest, it is necessary to move from passive teaching to active participation. [2, 3]

One of the key teaching methods is Inquiry-based Science Education. For example, simulation games where students "compete" in accurately measuring objects increase motivation. Another approach is the integration of real-world projects where students collaborate with companies to measure prototypes. According to studies (e.g., from the European Association for Metrology), such methods increase knowledge retention by 30-50%. In the context of 3D metrology, this means focusing on modern tools that students are familiar with from everyday life, such as 3D scanners in smartphones or optical systems in game consoles. [1, 4, 5]
Innovative approaches also include collaboration between disciplines. For example, combining metrology with artificial intelligence allows students to see a broader context. This makes metrology not only a science, but also a tool for solving global problems such as sustainable manufacturing or medical diagnostics.

Modern teaching of 3D metrology
Modern 3D metrology focuses on contact and non-contact measurements. Key technologies include:

- **Coordinate measuring machines (CMM)**

Coordinate measuring machines (CMMs) are the basis of 3D metrology. These devices measure points in space using a probe that moves in three axes. [2,3,5,7] In class, students can learn to program CMMs using software such as Zeiss Calypso, where they simulate measurements on virtual models. Example: Students design a measurement cycle for an automotive part, learning about tolerances and geometric deviations according to ISO 1101 (ISO GPS) standards.

- **Optical scanners and methods**

Optical scanning methods based on lasers or structured light enable rapid, contactless capture of 3D data. Devices such as ATOS from Zeiss or handheld scanners are used to digitize objects. [7, 8] In teaching, these technologies are integrated into laboratory exercises where students scan real objects (e.g., prototypes from a 3D printer) and analyze the data in software such as Zeiss Inspect. This increases interest because students see immediate results – a point cloud transformed into a 3D model.
Other optical methods include interferometry, which is ideal for measuring surface roughness using the Alicona device.

The use of artificial intelligence in teaching 3D metrology
Artificial intelligence (AI) is revolutionizing metrology by automating data analysis and predicting errors. In teaching, AI is integrated through machine learning (ML), where students train models to classify defects from 3D scans. For example, using libraries such as TensorFlow or PyTorch, students can create neural networks that detect deviations in measured data.
Genetic programming algorithms minimize measurement evaluation time, which students simulate in projects. Furthermore, AI helps interpret large data sets from optical scanners. This increases interest because students see the connection between metrology and trends such as big data and Industry 4.0.
Application example: In the course, students use AI to predict product quality based on 3D measurements, which motivates them to think interdisciplinarily.

Virtual and augmented reality in metrology
Virtual reality (VR) and augmented reality (AR) transform teaching into an immersive experience. VR allows students to "enter" a virtual laboratory where they can manipulate

CMMs or scanners without the risk of damaging real equipment. Software such as Unity or Frame VR, etc. is used to simulate measurements in a 3D environment.
AR, on the other hand, overlays digital information onto the real world. Using apps, students see virtual measurement points on a physical object, making it easier to understand optical methods. Innovative projects include AR in field measurement, where students use mobile devices to overlay tolerances on scanned objects.
These technologies increase engagement by making learning interactive—students can collaborate in virtual teams, simulate errors, and see results immediately. Studies show that VR/AR increases retention by 75% compared to traditional methods.

Using robots and programming via Visual Components
Robotics is a key element in modern metrology, where robots automate measurements. In teaching, we focus on robot programming using Visual Components software, which enables the simulation of industrial processes in a 3D environment.
Visual Components is a digital twin tool where students design robotic cells for 3D measurements. For example, they program a KUKA robot to manipulate objects during scanning. This involves learning about kinematics, trajectories, and sensor integration.
Innovative approach: Students create simulations where the robot collaborates with AI for adaptive measurement. This combines metrology with robotics, increasing practical skills and interest in interdisciplinary projects. Example: A project for automated measurement in the automotive industry, where students optimize the process through Visual Components.

Conclusion
Innovative approaches to teaching 3D metrology, such as the integration of AI, VR/AR, and robotics through Visual Components, are transforming this interdisciplinary science into an attractive field for students. This not only increases their interest but also prepares them for the future of the industry. Future research should focus on measuring the effectiveness of these methods in real courses. Metrology is thus ceasing to be just a theory and becoming a tool for innovation.

Acknowledgement
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PRODUCTION SYSTEM SIMULATION

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Abstract: Computer simulation is an experimental method which replaces the real system by a computer model. This model is subjected to experiments which are evaluated and optimized and results are re-applied to the real system.
Today, when computing performance is rapidly growing, there is a tendency of the occurrence of new techniques and methods which until recently were reserved only for very powerful computers with necessary team of highly qualified experts. Such technique is computer simulation.

Keywords: computer simulation, modelling, production, data.

Introduction

Computer simulation dates back to the period of warfare simulations, from where this methodology moved to space research. From these fields, advantages of computer simulation gradually moved to production and non-production systems.

Digital simulation model of production

By means of current software products of computer simulation it is possible to simulate almost any process in production as well as non-production areas. Current simulation means allow us to simulate continuous as well as discrete processes.

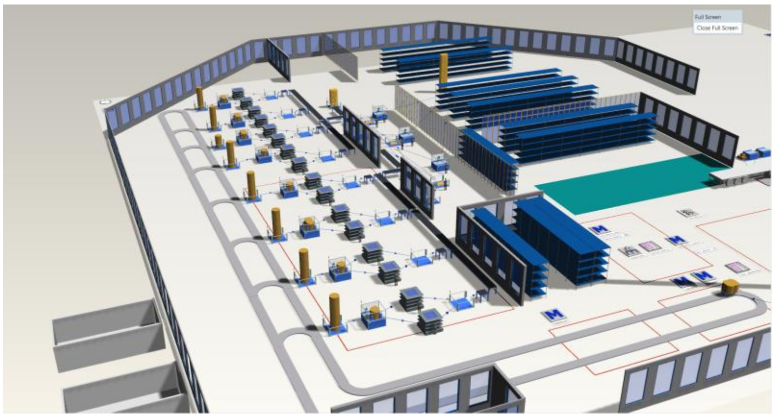

Fig. 1 Digital simulation model of production

The term process in this field encompasses anything that must be simulated. The subject of simulation can be, for example, mixing of solutions at various external conditions, supply of components for an assembly line, transport of components from the supplier to the consumer, simulation of new production lines.

In production systems of mechanical engineering, basic objectives of simulation as a method to study behaviour of a certain system through a computer or any other model and experiments can be divided as follows:

- analysis of existing production systems for improvement purposes,
- designing or verification of projects of new production systems.

The analysis of existing production systems can be classified as follows:
Determination of whether it is suitable to reconstruct or modify the existing production system;
Analysis of the production system behaviour under different production conditions;
Determination of how different control algorithms affect operation of the production system.

Tasks of the analysis of existing and projected manufacturing processes or verified projects of manufacturing processes are carried out by experiments with a simulation model through entering various input data – this simulates dynamics of the system state development.

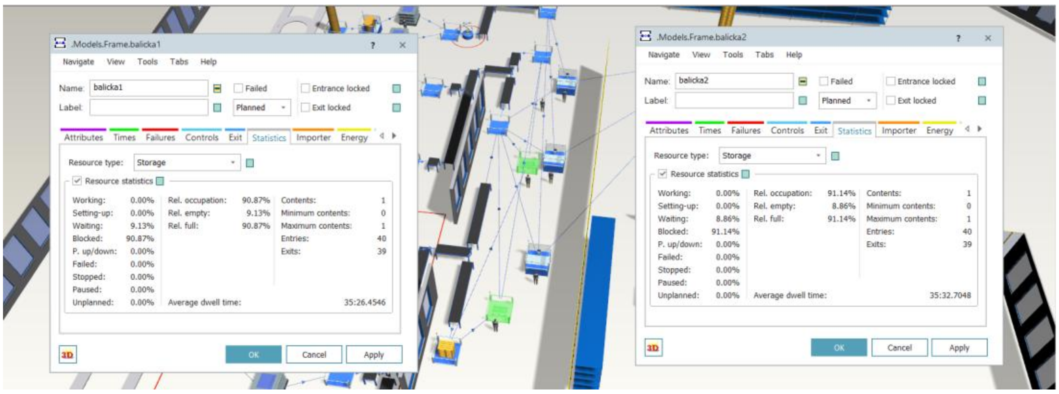

Fig. 2 Production line utilization in simulation software

When working with computer simulation, it is always necessary to bear in mind that the following question must be asked and, at the same time, answered: What should be the main objective of the required computer simulation? When searching for the answer to this question, it should be defined what do we want to found about a given manufacturing or non-manufacturing process through computer simulation. [3].

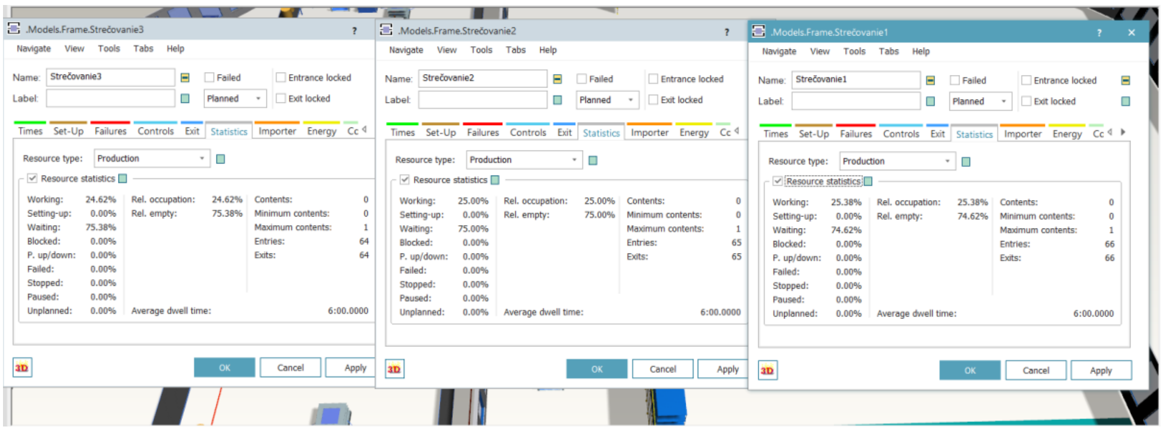

Fig. 3 Output from simulation SW in the form of production volume statistics

Main objectives of simulation may include, for example:

Finding a bottleneck in the company manufacturing process.
How can we increase throughput of the production or administrative system?
What is the maximum possible output from the production system?

One of the main advantages of current software products of computer simulation is the possibility to simulate the above-mentioned processes at time requested by the user. Simulation of the required real time within computer simulation takes only a few minutes. After simulation operation, each of the current simulation programmes provides sufficient amount of messages (so-called reports). Based on these reports it is possible to verify validity of the required main simulation objective. Advanced models can help find optimum solution at defined limiting conditions during short time.
An indisputable benefit of current simulation programmes is the fact that all such programmes are very user-friendly oriented. The majority of such simulation programmes is aimed to create simple models of manufacturing plants without any necessary programming knowledge. Detailed knowledge of relations between individual elements of the production system is necessary.
At the same time, it is very important to distinguish for what kind of real system we want to create a simulation model. Is the system to be simulated a pull-type system or a push-type system? (pull or push).
In order to create (programme) models, language that is very similar to Basic is often used. This programming language contains a large number of features which are easy to use when establishing a model. Simplicity in programming is very effective and useful in case of requested quick change of the simulation model. A simulation model can be changed almost on the spot, while actual model credibility is not affected.
Many simulation programs use icons during creation of a manufacturing system model. Icons build a so-called menu from which an icon can be chosen which represents a required element. If the element icon does not meet expectations of the author of the simulation model, own icons can easily by created in these programmes meeting author’s expectations. It is clear from the above-mentioned that a ready simulation model can visually exactly correspond to what the client expects. Simulation tools have developed to such a level that a third dimension can be added to the simulation model created in a two-dimensional environment. Visual representation of a production line by means of virtual reality extends possibilities of a simulation model coming closer to reality visually. When designing new production processes, virtual reality might be very important with respect to correct ergonomic arrangement of the production system.
Simulation processes, mainly those which are very application-specific, many times provide the user with a whole range of more or less useful and important data at the output from the simulation process. The user can choose those data which he or she considers most needed considering his or her aims. Outputs listed in a table are often very non-transparent even after reduction. As a result, many simulation systems need graphical representation of these outputs, for instance in graphs or histograms. An effective instrument which, in addition, enables the user to gain overview of reasons for bottlenecks and effect dynamics of the system state development during actual simulation, is the animation of simulation processes.
With methods such as computer simulations we need to consider another very important fact. Even the best simulation product is not omniscient and everything we are able to simulate by means of such a product always depends on the user creating the simulation model. Other decisive factors are the defined aim of the simulation, accuracy and reality of information resulting from the manufacturing process and entries of such information in the simulation

model. Already during model structuring, all simulation programmes need information and data which are often omitted when planning new manufacturing processes, or are considered irrelevant. At this point, it must be stated that incorrect input data result in faulty outputs from simulation models. We should consider that the issue of correct and up-to-date data is not the problem of a simulation programme. This issue, to a great extent, is dependent on the author of the simulation model. In engineering production systems, the majority of simulation model input data have the nature of random quantities or data which arose from statistic processing of set of measured values. These values are then implemented in models as theoretical divisions of probability or empirical divisions of multiplicity. Determination of suitable and correct parameters of these partitions is often more difficult than the actual arrangement of a model and experimentation.
At this occasion we must not forget another fact which affects simulation results as well. This is the effort of some authors to capture real situation in a simulation model to the last detail. Such effort prolongs the creation of the simulation model and the effort spent will not pay back in the form of increased accuracy of the simulation model. Sometimes it might even cause lower accuracy of the simulation model.

Conclusion

In manufacturing practice, a better result within the use of simulation tools can be achieved at project preparatory stages. Simulation applied at a preparatory stage can save huge amount of financial means. At the same time, given that data on the new system are needed to be entered into the simulation model, data are often required which are omitted during preparatory stage.

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GEARBOX DESIGN FOR ROBOTIC APPLICATIONS USING ADDITIVE MANUFACTURING

Rudolf JÁNOŠ – Jozef SVETLÍK – Jaroslav MELKO

Abstract: This paper presents the design and development of a cycloidal gearbox optimized for additive manufacturing. Several gearbox concepts were analyzed, with planetary and harmonic drives being excluded due to their complexity and strict tolerance requirements. The cycloidal gearbox was selected for its simpler geometry, robustness, and suitability for fabrication using FDM 3D printing. The design process included determining the transmission ratio, verifying the effective moment of inertia for controllability, and generating the cycloidal disc using parametric equations in SolidWorks. Special attention was given to the geometry to enable direct manufacturing without post-processing, while ball bearings were employed to improve efficiency and durability. A prototype was manufactured and successfully tested, showing favorable performance in terms of strength, reliability, and smooth transmission. The results demonstrate that cycloidal gearboxes can be effectively adapted for additive manufacturing, providing an accessible and cost-efficient solution for robotic applications.
Keywords: cycloidal gearbox; additive manufacturing; FDM 3D printing; robotic applications; parametric design

Introduction

The design and development of transmission systems for robotic applications represent a critical factor in achieving the required accuracy, performance, and durability in modern robotic systems. With the growing demand for robotic solutions offering higher efficiency and flexibility, the need for innovative approaches to the design and manufacturing of gear mechanisms has increased. Additive manufacturing, whether through 3D printing or other methods, provides new opportunities for producing complex and precise components with high efficiency and design flexibility. When designing a gearbox, several factors must be considered, including efficiency, technical constraints, and manufacturing feasibility. The first step is a thorough analysis of the gearbox requirements, such as torque, accuracy, and size. Since the gearbox will be produced using 3D printing, its size must be carefully evaluated. Several options were considered, including planetary, harmonic, and cycloidal gearboxes [1].

Planetary gearboxes feature a complex structure with multiple gears and components. Manufacturing them through 3D printing poses significant challenges in achieving the geometric tolerances and fine details of the gears[1]. Additionally, their frequent operation under high speeds and loads requires materials with high strength, which may be problematic in additive manufacturing. For these reasons, planetary gearboxes are considered difficult to produce using 3D printing [2].

Harmonic gearboxes were also considered. However, their design involves a large number of small, precisely shaped components, including flexible elements. Additive manufacturing of such parts would demand very high accuracy and detail, which can be difficult to achieve, while also being costly and time-consuming. Therefore, simpler and less demanding designs are often preferred. Based on this reasoning, a cycloidal gearbox was selected.

Cycloidal gearboxes offer several advantages for additive manufacturing. Their relatively simple design includes fewer components and moving parts compared to other types, which allows for easier production and assembly. Another advantage is their lower precision requirement during manufacturing and assembly. Due to the absence of conventional gear teeth, cycloidal gearboxes require less stringent geometric tolerances, simplifying the printing process. Despite this, they still provide suitable transmission ratios and efficiency for many applications. Their compactness combined with robustness makes them capable of handling significant loads and resisting wear [3].

For the fabrication of the cycloidal gearbox, Fused Deposition Modeling (FDM) technology was chosen due to its accessibility, relatively low cost, and wide availability of materials with sufficient strength and durability. Modern FDM printers can achieve adequate precision and detail, which is critical for the proper functioning of the gearbox. Some advanced FDM systems also allow multi-material and multi-color printing, which may further enhance functionality. Additionally, FDM printers are known for their reliability and robustness, making them suitable for long-term production of complex mechanical components such as cycloidal gearboxes. For these reasons, FDM was selected as the most appropriate method for this work, providing an efficient, accurate, and reliable approach to manufacturing.

Problem Statement

Modern robotic systems require compact, precise, and efficient transmission mechanisms. Conventional gear designs, such as planetary or harmonic gearboxes, often pose challenges for rapid prototyping and cost-effective manufacturing due to their complexity and strict geometric tolerances. There is a need for a gearbox solution that combines reliability, ease of manufacturing, and suitability for additive manufacturing technologies.

Research Objective

The objective of this research is to design, manufacture, and test a cycloidal gearbox optimized for 3D printing. The study aims to evaluate its performance, including transmission efficiency, load capacity, and dynamic behavior, while demonstrating the feasibility of using FDM additive manufacturing for producing complex robotic components.

Methods and Methodology

The design of a cycloidal gearbox is determined by four key input parameters that define the size and geometry of the cycloidal disc: the shaft eccentricity, the number of rollers, the roller diameter, and the pitch circle diameter of the roller placement. In designing individual components, it is also essential to maintain the minimum wall thickness of printed parts. For most common desktop FDM printers, a minimum wall thickness of approximately 0.8–1.0 mm is recommended [4,5].

The first parameter to be determined was the transmission ratio. Establishing the required transmission ratio for robotic applications must be based on a combination of the system’s mechanical and dynamic requirements. The procedure can be summarized in the following steps:

- **Load (torque, force):** the torque required for the robot to perform the given task (e.g., lifting a payload, manipulation, pushing).
- **Speed of motion:** the velocity at which the end effector or robotic link is expected to move.
- **Accuracy and stiffness:** higher gear ratios increase accuracy but reduce speed.

To determine the required output torque:

$$M_{OUT} = F\, r_M \tag{1}$$

To determine the required output torque, the next step is to establish the desired rotational speed of the robotic arm. Once both torque and speed requirements are defined, the necessary transmission ratio of the gearbox can be calculated:

$$i = \frac{n_{motor}}{n_{out}} = \frac{M_{out}}{M_{motor}\, \eta} \tag{2}$$

i = transmission ratio

n_{motor} – motor speed

n_{out} – required output speed

M_{motor}– nominal motor torque

η – gearbox efficiency (0.85-0.95)

In robotic applications, it is also necessary to verify the system dynamics to ensure controllability of the drive. The moment of inertia of the robotic links, reflected to the motor shaft, must remain within acceptable limits to guarantee stable and efficient operation.

$$J_{eq} = \frac{J_{load}}{e^2} + J_{motor} \tag{3}$$

J_{eq} = (3-10)

Jeq - effective moment of inertia

o generate the shape of the cycloidal disc, the curve creation tool in SolidWorks was used, applying equation-driven curves. Parametric curves operate in such a way that each point on the curve is defined by a parameter. Two equations are used: one for the x-coordinate (Eq. 4) and one for the y-coordinate (Eq. 5). These equations contain parameters that determine the position of each point on the curve. This approach allows for greater flexibility and more complex geometries, as it enables independent control of the x- and y-coordinates of the curve.

X = (R*cos(t))-(Rr*cos(t+arctan(sin((1-N)*t)/((R/E*N)-cos((1-N)*t)))))-(E*cos(N*t)) (4)

Y = (-R*sin(t))+(Rr*sin(t+arctan(sin((1-N)*t)/((R/E*N)-cos((1-N)*t)))))+(E*sin(N*t)) (5)

where
i – transmission ratio
N – number of rollers
n – umber of “teeth”
Rr – roller bearing diameter

R – pitch circle diameter
E < Rr – eccentricity

To reduce computational demand during simulation, it is recommended to generate only half of the curve and then mirror it.

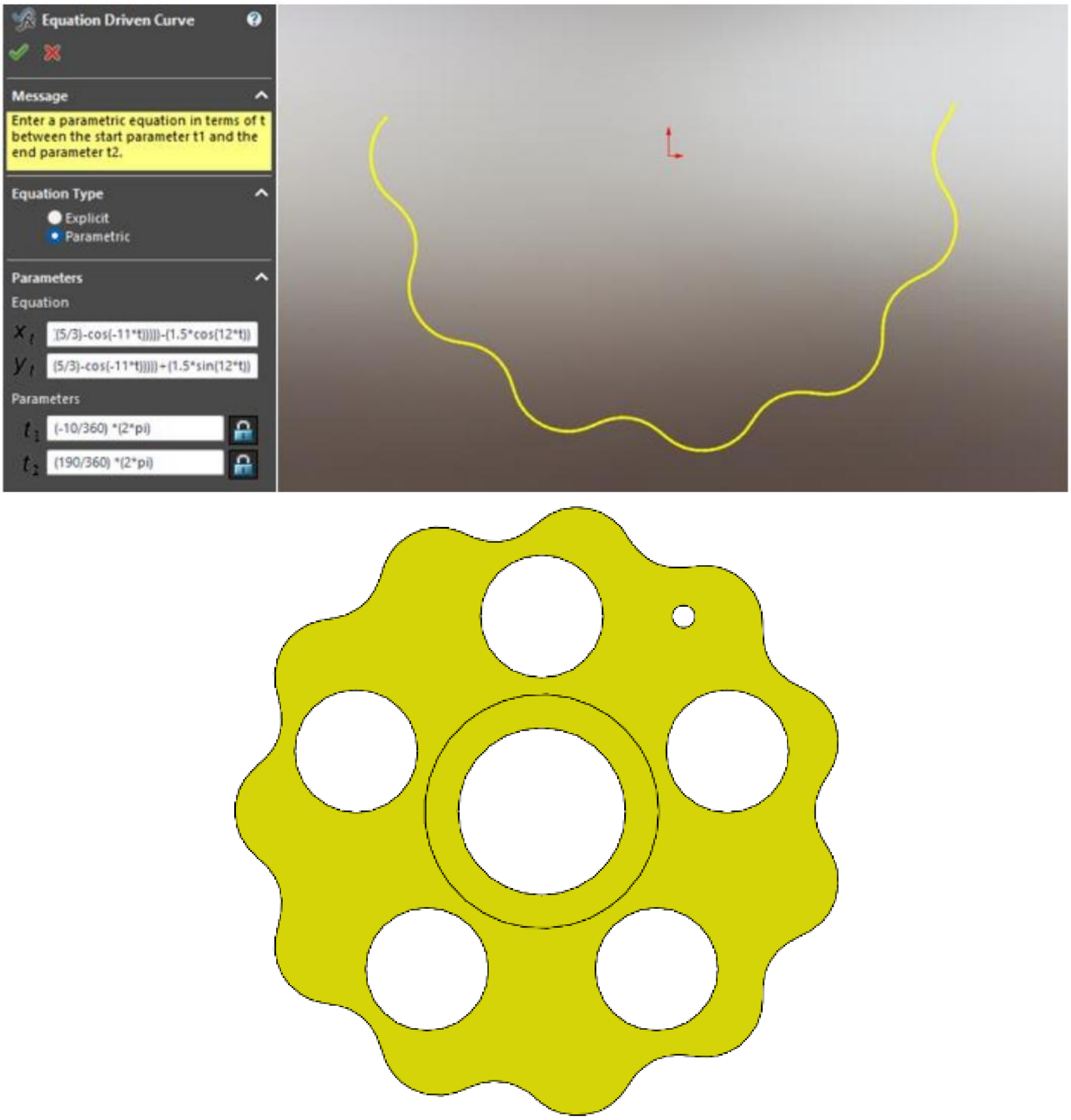

Fig. 1 2D Cycloid Generated Using Parametric Equations

Based on the generated cycloid, the remaining components of the cycloidal gearbox were designed. Particular attention was given to geometries that would enable 3D printing without the need for additional post-processing. For reasons of strength and improved efficiency, ball bearings were selected for the moving parts. An exploded view of the cycloidal gearbox is shown in Fig. 2.

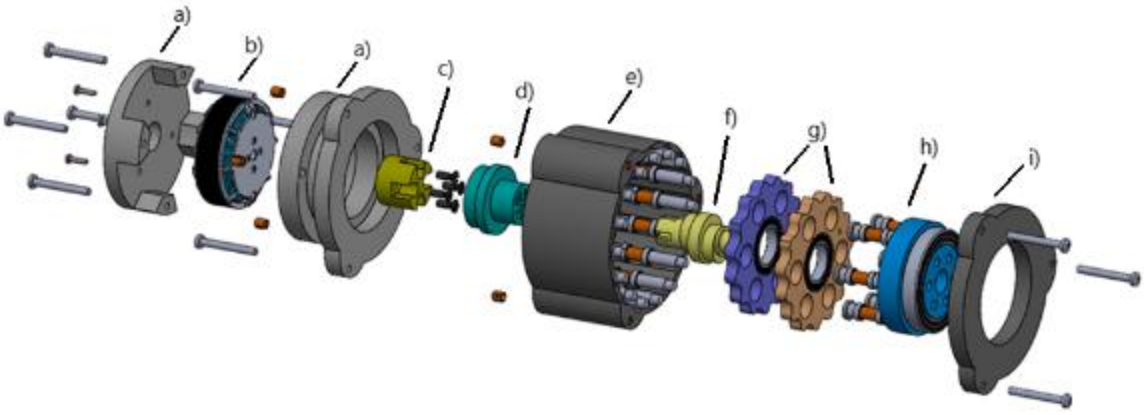

Fig. 2 Exploded View of the Cycloidal Gearbox
a) motor housing; b) housing cover; c) electric motor; d) input shaft; e) coupling; f) eccentric shaft; g) bearing seat; h) 2× cycloidal disc; i) output flange; j) cover

The proposed cycloidal gearbox was subsequently manufactured and tested in practice. The prototype demonstrated very good functional properties, such as smooth and stable transmission, minimal backlash, and reliable load transfer. The use of ball bearings in moving parts contributed to higher efficiency and reduced frictional losses, while the compact design maintained sufficient robustness and durability. The gearbox proved to be easy to assemble, and no significant post-processing of 3D-printed components was required. These results confirmed that the selected design approach, combined with FDM technology, is not only feasible but also provides a cost-effective and accessible solution for robotic applications requiring precision and reliability.

Conclusion

This work demonstrated the design and development of a cycloidal gearbox optimized for additive manufacturing. Among various gearbox types, the cycloidal design was selected due to its relatively simple geometry, reduced requirements for geometric tolerances, and suitability for fabrication using FDM technology. The methodology included determining the transmission ratio, verifying the effective moment of inertia for dynamic stability, and generating the cycloidal disc shape through parametric equations in SolidWorks. Special emphasis was placed on designing components that could be manufactured without post-processing, while ball bearings were employed to enhance strength and efficiency.
The results highlight that cycloidal gearboxes can be successfully adapted for 3D printing, providing a cost-effective, reliable, and accessible solution for robotic applications. Future work will focus on experimental testing, material optimization, and performance evaluation under real operational conditions to further validate the proposed design.
Future research will focus on further optimization of the cycloidal gearbox for robotic applications. This includes exploring alternative materials suitable for 3D printing to enhance strength, durability, and thermal stability. Experimental studies under varying load and speed conditions will be conducted to validate simulation results and assess long-term reliability. Additionally, multi-material printing and advanced FDM techniques will be investigated to improve performance and reduce wear. Integration of sensors for real-time monitoring of torque, temperature, and vibration is also planned, aiming to enable predictive maintenance and adaptive control in robotic systems. Finally, the scalability of the design for larger or more

complex robotic applications will be examined to expand the applicability of the gearbox in diverse industrial settings.

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ANALYSIS OF SECTIONAL WIRES PRODUCTION PROCESSES USING THE EXAMPLE OF AN EXISTING ENTERPRISE

Dariusz MICHALSKI – Bartosz SEWIELSKI – Marek KLIMENT

Abstract: This article analyzes production processes using the example of sectional hoses manufactured by Voss Automotive Polska. Defects were observed during production, and the causes of their occurrence had to be identified. A series of analyses and studies were conducted, which contributed to finding solutions to the problem. Optimization solutions were implemented to help eliminate the occurring irregularities. An in-depth analysis of production operations using appropriate tools, including the 5xWhy method, allowed for the determination of the causes of the problem. Analyses for two different variants of the problem identified the causes and ways to counteract the unfavorable situation.
Keywords: sectional wires, 5xWhy method, production process, cable chamfer.

3. Identifying the causes of sawing problems using the 5xWhy method

This article presents the authors' efforts to analyze the problem. A process analysis was conducted, looking for inconsistencies during production. After analyzing each production step, an irregularity was detected during the final production step during cutting. During problem solving, it was determined that a solution could be found in the use of a modernized chamfering tool, which would improve cutting. The chamfering tool was modernized. Potential design changes were suggested to enable cutting in the plane of the cable cross-section. After the cutting system was rebuilt, a cutting test was conducted on over 2,000 cables, which was successful [3]. The cables met quality parameters. Suggested improvements could improve work comfort at the workstation. Using a new device with a different support port, the cables limit cable position changes during cutting. Cutting requires a firm grip on the cable and control of the cut while eliminating the excess created on the saw. Additionally, introducing better lighting and height adjustments that can be adjusted to the operator's preferences could improve workflow and quality. To analyze the problem of crooked cable cutting, a solution was analyzed using the 5xWhy method. The analysis concerns the cutting curve for two different situations. The analysis allows us to understand the causes of the problem and allows for the introduction of optimization solutions [1, 7]. Figure 1 shows the analysis of the problem for cables with a 4mm difference in diameters in a single chain. The saw jaws can only grip one diameter in a single chain. The above analysis indicates that the problem with incorrect saw cutting is caused by improperly designed gripping clamps. Key causes include designing the clamps for conductors of uniform diameter, which resulted from a lack of prior experience and reports of varying conductor diameters within a single chain. Following analysis, the solution to the problem is to outsource the production of gripping clamps designed to accommodate the varying diameters within a single chain. Figure 2 shows the problem analysis for conductors where the corrugated section is too close to the tulip, the saw cutting point. The saw clamp simultaneously grips the section with the corrugated section and the segment near the tulip. The identified causes of the problem suggest that the difficulty in stabilizing the cut on the saw is related to the clamps not gripping the cable properly, which in turn is due to the cable design. Designing special jaws may not be sufficient, so other options are being considered. After analysis, two solutions emerge to address the issue. The first is to contact the customer to discuss the situation and develop a collaborative solution. The second option is to consider introducing an additional station that could improve the cutting process.

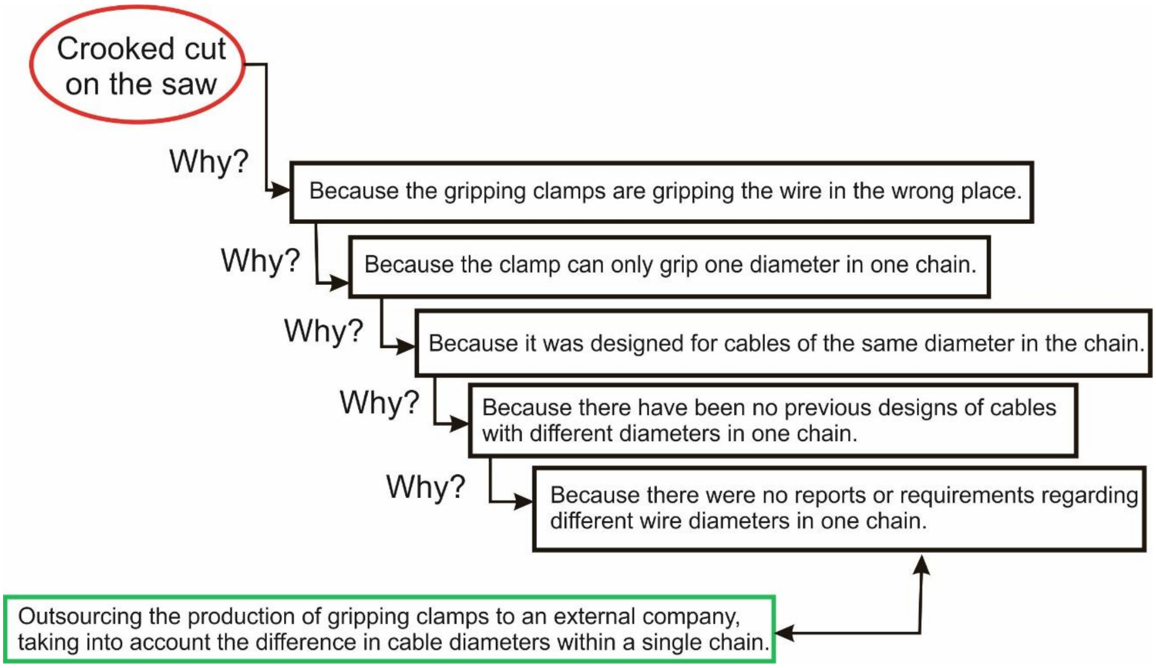

Fig. 1. Problem with stabilizing the cut on the saw, variant 1 [6].

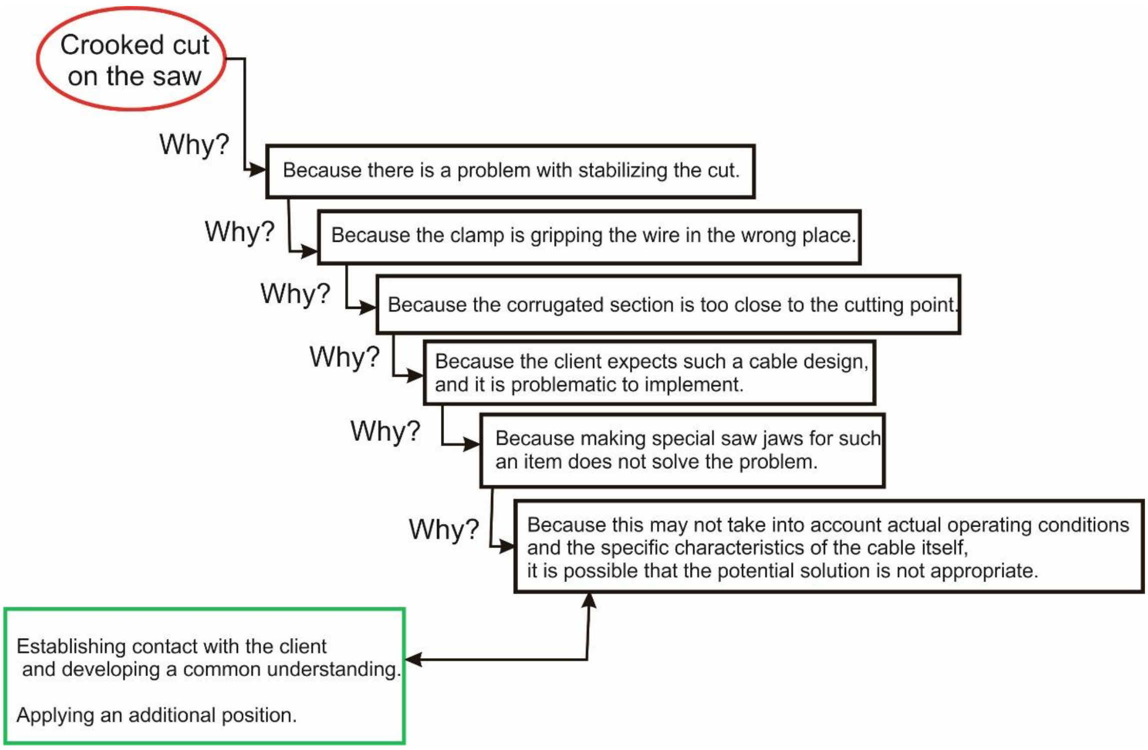

Fig. 2. Problem with stabilizing the cut on the saw, variant 2 [6].

4. Saw cutting accuracy problems: root cause analysis

The problem with machine cutting is that the saw, specifically the cutting system, is not designed to handle complex products, which impacts the cutting process. This is due to the high demands and complex structure of the cable, which is dictated by the specific production process. The problem concerns the clamps that grip the cable during cutting. Difficulties that arise include differences in diameter within a single chain, or the complex structure of the cable due to the proximity of the corrugated section to the tulip, the point where the saw cuts. The corrugated section has a larger outer diameter than the tulip. Therefore, the jaws in the cutting machine, instead of gripping the cable at the tulip, grip the corrugated section. This causes the cable to yield and deform during cutting, preventing the knife from cutting perpendicularly [4]. The photograph shows the dimensional differences in areas that are problematic for the saw to operate correctly, as the jaws grip the cable in Figure 3.

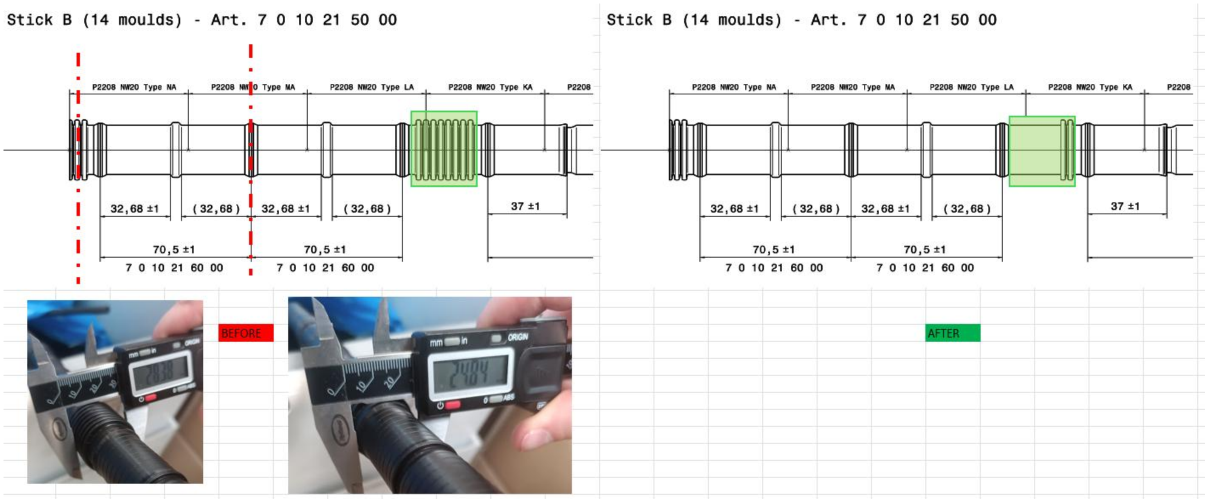

Fig. 3. Diameter measurement of the corrugated part and the tulip.

After analyzing the machine's design and potential upgrades, the solution to the problem could be to use different gripping clamps. An example of such an operation is the project for the BMW G68 with the problematic design 7011093600 and 7010214800. To hold the pipe before cutting, different gripping clamps were manufactured by an external company. Figure 4 shows the solution to the problem for two parts using different clamps.

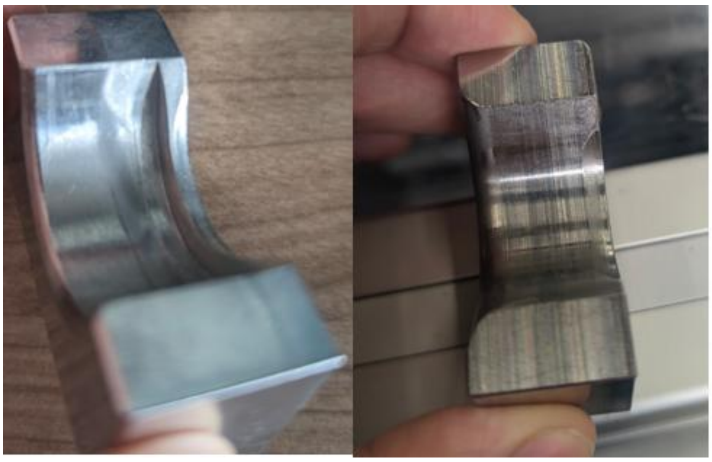

Fig. 4. Modified calipers.

Removing or reducing the corrugated section will help stabilize the cut using dedicated clamps. The client's requirements dictated that the project be completed as expected. Despite modifying the machine jaws to create ridges that insert between the tulip and the corrugated section to hold the cable in place, the problem persists. The cable collapses and shifts during cutting. This results in skewed cuts. A solution could be the introduction of a modular workstation. At the new workstation, the future operator will be able to perform surface leveling after machine cutting. The problem only affects selected product numbers. Saw cutting caused uneven edges, which prevented the batch from being shipped to the customer due to quality issues. A prototype solution, a separate workstation, was implemented in the production process of sectional cables for testing purposes. During the production of the problematic cables, it was determined that they needed to be placed in a prototype station, located next to the cutting machine, at the end of the sectional cable production process. The different cable structure prevents proper cutting, creating defects that the organization calls "noses." The cutting machine does not cut perpendicularly to the cable axis. The cutting problem occurs due to the machine's design and the specific structure and characteristics of the cable [2]. The photograph shows the cable, highlighting the problematic and critical areas during the cutting stage in Figure 5.

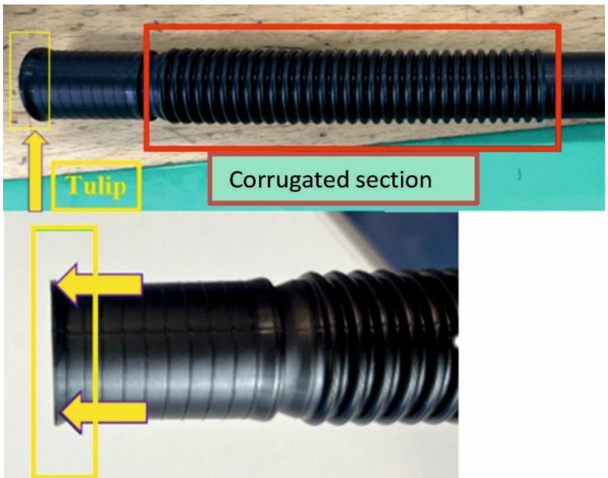

Fig. 5. Corrugated section and tulip.

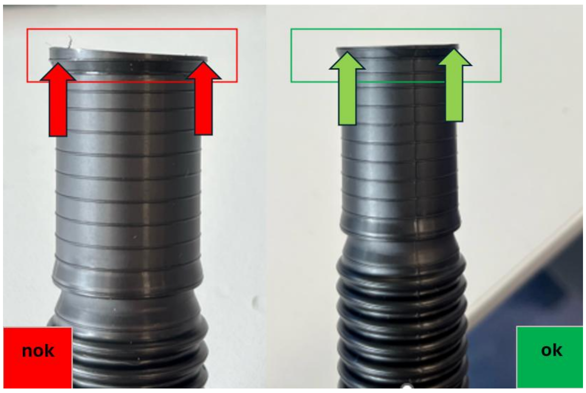

Fig. 6. Cable with a defect nok, and without a defect ok.

Figure 6 shows two sectional cables. The "nok" designation indicates that the cable has a defect. This is the cable before the cutting operation on the prototype station. The "ok" designation indicates that the part complies with the requirements after the cutting operation for improvement. This cable can be continued.

5. Implementation of a station to improve sectional cable cutting

A solution that will help eliminate this problem is to create a small station adapted for cable repair. Selected items require re-cutting of the uneven edge. This solution is easy to implement and relatively cost-effective. This new station is a prototype solution. The photo shows a prototype station for cable repair, shown in Figure 7 [5].

The cutting structure and power supply were modernized due to the different operations performed on the same device. Components of the cutting system were modified. This work was undertaken by the maintenance department, mechanics, and specialists. The modernization included the blade sleeve, blade, and bearing-mounted shaft on which the cable is mounted. The previous blade, which was used for chamfering, was mounted at a different angle, which is why the operation on this device was called chamfering. After the modernization, the tool is no longer used for chamfering, but for cutting. A new blade was manufactured, mounted at a right angle to the cable axis. The shaft was replaced with a larger one due to the larger internal diameter of the cable. The machine's previous use was for chamfering cables with a small internal diameter. The shaft diameter must be matched to the cable's internal diameter to prevent the shaft from rotating, which would cause friction on the inner wall of the cable. The shaft itself is mounted on bearings but requires adjustment to the cable diameter. The shaft is designed to rotate on a bearing, not on the contact between the inner walls of the cable. This situation could cause friction on the internal surfaces, which is not permitted. The cutting system is housed within a protective housing. This ensures safe operation and facilitates the removal of cutting waste into a container. The photo shows an example of the modernized cutting element in Figure 8 [8].

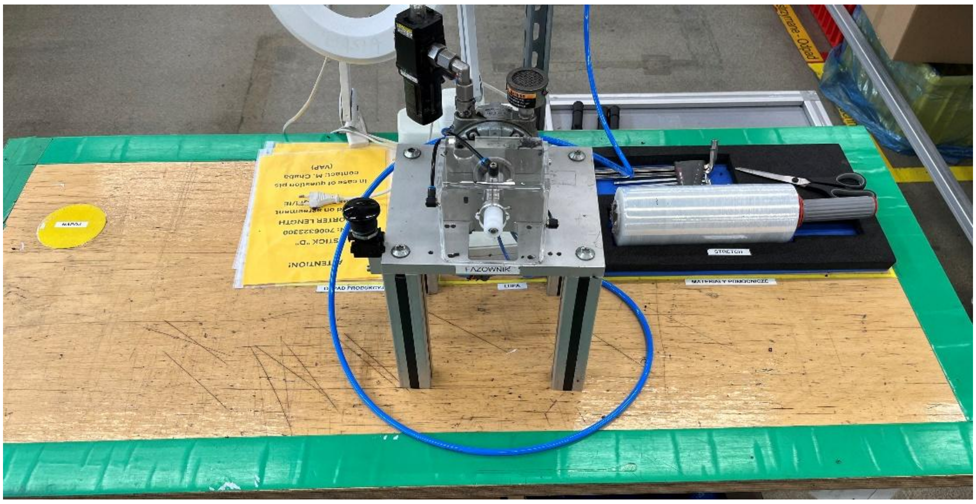

Fig. 7. Cutting improvement station.

The cutting improvement step is simple, quick, and effective. Figure 9 shows the wire-tool system during the prototype cutting process. During cutting, the surface at the tulip is corrected. This is the area designated for cutting. The operator holds the cable in their hands and moves it towards the cutter while the machine is operating; the rotating blade corrects the surface. Before cutting, review the work station instructions prepared for the prototype and perform all necessary visual inspections to ensure proper operation of the systems and rotating components. With new solutions and modifications, greater vigilance and inquisitiveness should be maintained during testing and verification [8].

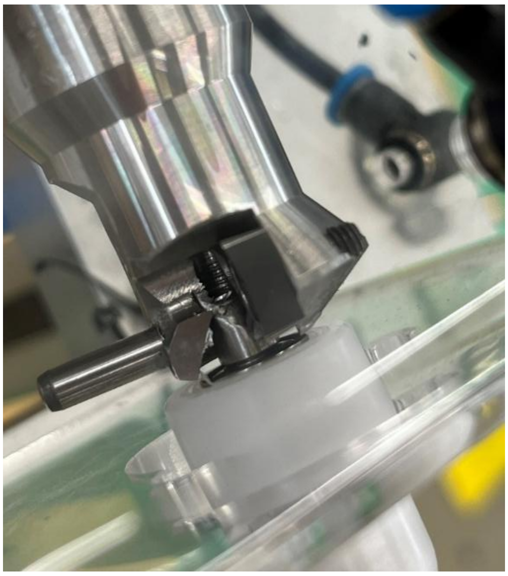

Fig. 8. Modernized cutting element.

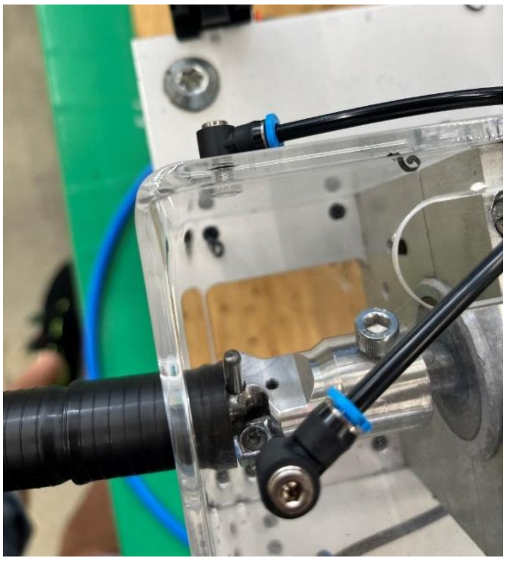

Fig. 9. Cutting process on a prototype.

The benefits of introducing an additional station allow for the production of cables for the customer that meet quality parameters. Creating such a station itself is much cheaper than purchasing a new dedicated cutting machine for a selected group of cable products. The easiest and most affordable solution is to introduce a prototype station adapted to this type of work. The availability of replacement machines allows for the creation of a practical and cost-effective prototype that eliminates or minimizes the emerging problem [9].

Conclusions

This article presents the author's efforts to analyze the problem. The process was analyzed, looking for inconsistencies during production. After analyzing each production step, an irregularity was detected during the final stage of production during cutting. It was determined that the chamfering device needed to be modernized to improve cutting. After rebuilding the cutting system, a cutting test was performed on over 2,000 wires, which was successful. Samples of wires, both before and after cutting, were sent to the laboratory for further analysis. The 5xWhy method was used to solve the problem. One solution was to commission an external company to manufacture saw jaws with a different design that allowed for proper gripping of the wire during cutting, an alternative solution to the crooked cut. The second solution was to introduce an additional station to improve the cutting of selected components. A station was implemented to improve cutting, located at the end of the production line. This successfully contributed to the elimination of defects and an increase in the number of good pieces.

Acknowledgments

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POSSIBILITIES FOR THE USE OF BASALT FIBER MATERIALS IN AUTOMOTIVE AND AEROSPACE INDUSTRY

Peter KAŠŠAY – Michal Hovanec – Samer AL-RABEEI – Ivana KOLÁRIKOVÁ – Volodymyr Tymofiiv

Abstract: Basalt materials represent a significant innovation in the field of modern materials due to their unique properties such as high strength, light weight and resistance to extreme conditions. Their environmental benefits, low energy intensity in production and use of renewable resources make them an attractive alternative to traditional materials such as steel or carbon fiber. Basalt materials represents an innovative solutions and contribute to sustainable development. The importance of basalt materials will thus grow with further technological and ecological advances. The aim of the article is to briefly introduce lightweight progressive materials used in the automotive and aerospace industries, with an emphasis on the use of materials with basalt fibers.
Keywords: basalt, materials, comparison, transport industry.

Introduction

The transportation industry, is currently undergoing a profound transformation. This change is being driven by the rapid advancement of progressive technologies and the introduction of innovative materials. These developments are not only enhancing the efficiency and sustainability of transport systems but also addressing some of the most pressing challenges of our time, such as climate change, urban congestion, and energy consumption. The integration of these new technologies and materials is paving the way for a more resilient, efficient, and sustainable future in transportation [1]. Another area where progressive technologies are making a significant impact is in the development of sustainable materials for transport applications. Lightweight materials such as light alloys (aluminum, titanium, and magnesium alloys), conventional high strength steels (HSS), advanced high-strength steels (AHSS) and carbon-fiber reinforced polymers (CFRPs), are being increasingly used in the construction of vehicles and infrastructure to improve fuel efficiency and reduce emissions [2-6]. These materials not only offer superior strength-to-weight ratios but also contribute to the overall sustainability of transportation systems by enabling the design of more energy-efficient vehicles. With constant developments in technology and demands for sustainability and efficiency, transport is facing radical changes in the use of materials. Advanced materials are a key factor in reducing emissions, increasing safety and improving the performance of transport vehicles.

This article looks at some of the latest materials in transport that have the potential to shape the future of the industry, and concludes by linking it to the importance of basaltic materials. Basalt or basalt fibers are inorganic fibers produced from molten basalt rock. They represent an innovative material with extraordinary properties and a wide range of applications [7]. Their eco-friendly production, excellent mechanics, durability and recyclability make them an attractive alternative in various industries [3].

Use of new materials in automotive and aerospace industry

The transport industry is on the threshold of a new era, driven by the introduction of advanced technologies and innovative materials. From electrification and autonomous vehicles to sustainable materials and the integration of the Internet of Things, these advances are poised to change the way we transport people and goods. As these technologies continue to evolve, they hold the promise of creating a more efficient, sustainable and resilient transport system of the future [1].

Aluminum is an increasingly popular material in the automotive industry due to its light weight and high strength. The use of aluminum alloys makes it possible to reduce the weight of cars, which directly reduces fuel consumption and CO_2 emissions [8-9].

Carbon fiber, or carbon fiber, is considered one of the most advanced materials for the construction of lightweight but extremely strong parts. This material is mainly used in sports and luxury cars, as well as in aerospace, where weight and strength are key. Although carbon fiber is more expensive than traditional materials, it is growing in importance due to the requirements for weight reduction and increased performance of vehicles [10].

Glass fibers are used in the automotive and aerospace industries mostly as fiber-reinforced plastics (FRPs) that reduce vehicle weight and improve fuel efficiency. In the automotive sector, glass fibers are in body panels, bumpers, and interior components, while in aerospace, they are used for fuselages, wings, and specialized thermal protection. The material's high strength-to-weight ratio, durability, cost-effectiveness compared to carbon fiber, and insulating properties make it ideal for these demanding applications [11-12].

Aramid fibers offer high strength and modulus, and they are used as reinforcement in advanced composites. Aramid fibers have also low density and thermal conductivity, high heat resistance and chemical resistance. There is an increased demand for aramid fibers with the development of technology [13-14].

Magnesium alloys have similar properties to aluminum but are even lighter. They are used in various parts of cars and aircraft where weight is a critical factor. In the aerospace industry, magnesium alloys are used to reduce the weight of aircraft, thereby reducing fuel consumption and extending aircraft range. Although this material has potential, it is limited by its susceptibility to corrosion and higher production costs [15].

Titanium is a lightweight and very strong material that is often used in the aerospace industry, particularly in aircraft and engine designs. Titanium alloys have excellent resistance to high temperatures and corrosion, making them ideal for use in engines and other parts that are exposed to extreme conditions. Although titanium is more expensive than aluminum, its properties allow it to improve the safety and durability of aircraft [16].

Self-healing materials represent a new development in the field of advanced materials for aerospace. These materials could "heal" small damages or micro-cracks without the need for human intervention. This kind of technology can dramatically increase aircraft safety, reduce the need for maintenance and extend the life of individual components. It is currently being tested mainly on composite structures in aircraft [17].

Eco-friendly materials. With increasing pressure to reduce the environmental impact of transport, the industry is looking for alternatives to traditional materials. Bio composites are one of the materials that have the potential to replace plastic or metal components in various transportation systems. These materials are made from natural fibers, such as flax or hemp, combined with biodegradable polymers. The advantage of bio composites is their ability to reduce the carbon footprint and ecological impact of transport systems [18-19].

In the context of environmentally friendly and efficient materials, the use of basalt fibers is increasingly being considered as an innovative solution in various transport sectors. Basalt fibers, which are obtained by melting natural basalt, offer an excellent strength-to-weight ratio, high temperature and corrosion resistance as well as excellent chemical stability. The use of basalt fiber can replace traditional glass and carbon fiber, offering a more affordable and environmentally friendly alternative. For example, in the automotive industry, basalt fibers can be used to make lightweight and strong composites for bodywork or interior components, reducing vehicle weight and therefore fuel consumption [20].

Due to their high heat resistance, basalt fibers are also suitable for the aerospace industry, where they can be used in parts exposed to high temperatures, such as engine cowls or insulation materials [21].

Basalt fibers production technology

The first attempts with basalt fiber dating back to the beginning of the 20th century, significant development of production took place after the Second World War [22], when new technologies began to be used and interest in the properties of basalt fibers grew.

Basalt fiber is made from basalt Fig. 1, a volcanic rock with exceptional properties. It is mined in quarries and crushed to a fine grain size, which is further treated and stripped of impurities. The largest basalt mines for producing basalt fiber are located in Russia, Ukraine, and Georgia [23].

Fig. 1 Basalt rock. [24]

Basalt fiber production process [25-29] is illustrated with a simplified diagram in Fig. 2. As raw material, only basalt is used (1) no other additives are needed. The melting of basalt takes place in a furnace at temperatures of around 1500°C. Electronic heating, natural gas flame heating or a combination of both can be utilized. The melting itself usually consists of first stage (2) and second stage (3) where the temperature of melt is controlled more precisely. The melt then comes out trough platinum–rhodium alloy bushings, with resistance heating allowing to further regulate the temperature. The melt passes through nozzles, forming thin filaments which then solidify rapidly on contact with air (4). The basalt fibers have amorphous structure due to rapid quenching process. The diameter of basalt fibres is controlled by varying the drawing speed and melting temperature **Chyba! Nenašiel sa žiaden zdroj odkazov.**. Then the fibers go t hrough sizing where protective and functional additives are applied (5), strand formation (6) and tensioning (7). Finally, the fibers are winded in rovings (8).

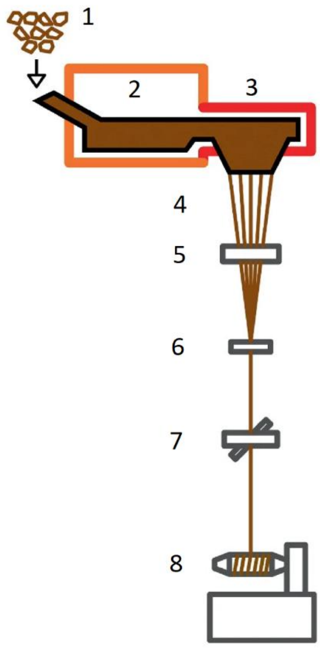

Fig. 2 Simplified continuous basalt fiber production schematics [26]

Basalt fibers are very thin, their diameter vary approximately between 9 and 23 micrometers for standard fibres but super-thin basalt fibers may have diameters between 1 to 3 micrometers [29]. The properties such as strength and temperature resistance depends on the thickness of the fibers and the method of manufacture. These fibers can either be used as a base for other composite materials or can be spun into fabrics which are then used for various technical and construction purposes. Basalt fiber end products can take a variety of forms, including fabrics, rods, mats or composite panels (Fig. 3).

Fig. 3 Examples of basalt fiber products a) rovings, b) woven fabrics, c) needlefelt, d) meshes [24]

These products are then tested for various mechanical and physical properties such as tensile strength, corrosion resistance and resistance to high temperatures. Testing is essential to ensure the quality and reliability of materials before their commercial use. Certification is also an important part of this, ensuring that products meet international standards and are suitable for specific applications, for example in construction or transport.

Properties of basalt fibers and comparison with other materials

An overview of continuous basalt fiber properties compared with other materials used as reinforcement of composite materials is shown in Tab. 1. The data in table was collected from several sources **Chyba! Nenašiel sa žiaden zdroj odkazov. Chyba! Nenašiel sa žiaden zdroj od kazov.**, [32-34].

Tab. 9 Comparison of basalt fiber and other materials properties

Properties	Materials				
	Basalt fiber	Glass fibers		Carbon fiber	Aramid fiber
		E-Glass	S-Glass		
Density [kg.m^{-3}]	2650–3050	2550–2620	2460–2490	1780	1440
Tensile strength [GPa]	3.0–4.84	3.1–3.8	4.59–4.83	3.5–6.0	2.9–3.4
Modulus of elasticity [GPa]	79.3–93.1	72.5–75.5	88–91	230–600	70–140
Elongation at break [%]	3.1	4.7	5.6	1.5–2.0	2.8–3.6
Basal diameter [μm]	6-21	6-21	6-21	5-15	5-15
Working temperature [°C]	-260–880	-60–350	-60–300	<2000	<250
Softening point [°C]	960	850	1056	-	-
Thermal conductivity [W·m^{-1}·K^{-1}]	0.031–0.038	0.034–0.040	0.034–0.040	5–185	0.04–0.13
Thermal expansion coeff. [10^{-6}.°C^{-1}]	8.00	5.40	29.00	0.05	-5.7 – -4
Energy consumption [MJ.kg^{-1}]	10.8–14.4	21.6–28.8	21.6–28.8	100–900	
Price [USD.kg^{-1}]	2.5–3.5	0.75–1.2	5–7	30	25

According to data presented in Tab. 1 we can compare the usability of fiber materials.

Regarding density and basal diameter, basalt fibers have similar properties as glass fibers. Carbon and aramid fibers have lower density and basal diameter, thus they are lighter.

Basalt fibers have higher tensile strength than E-glass fibers but and similar to S-glass fibers. Regarding to tensile strength carbon fibers are the strongest.

The elongation at break of continuous basalt fibers is higher as for carbon fibers but smaller than the values of glass fibers.

The working temperature range of basalt fibers is superior to glass fibers. Basalt fibers can be used from -260 to 880 °C this makes them suitable for application in aerospace industry or as insulation material [31-32].

The production price of continuous basalt fiber is higher than the production price of E-glass fibers and lower as of S-glass fibers. But it is significantly lower than the production price of carbon and aramid fibers.

The energy consumption during production of continuous basalt fibers is the lowest of all materials presented in Tab. 1 which makes them the most environment friendly regarding energy consumption.

Compared to other fiber materials used as reinforcement of composite materials, we can summarize the properties of continuous basalt fibers as follows:

- Lightweight construction with remarkable strength
- Excellent thermal insulation properties
- Very good corrosion resistance [31]

• Environment friendly production
• Favorable production price

Conclusion

Basalt materials represent a significant innovation in advanced materials that are increasingly used in a variety of industries including construction, aerospace, transportation and energy. Their unique properties such as high strength, light weight, corrosion, heat and chemical resistance make them ideal for applications where extreme conditions and durability demands are required. Basalt's environmental credentials, especially when compared to traditional materials such as steel, aluminum or carbon fiber, make basalt an attractive alternative for sustainable development. Their production process is less energy intensive, and the raw material comes from renewable natural resources, which reduces the ecological footprint. In addition, their growing popularity in industry is contributing to reducing operating costs and improving the efficiency of various systems. In the field of education, basalt materials provide multidisciplinary opportunities to link science, engineering and environmental education. Their study promotes innovation, the development of sustainable solutions and the development of practical skills in modern technologies. Given this knowledge, we can assume that basalt materials will continue to play a key role in the future of technological and environmental progress. As basalt fibers are increasingly used in industry, it is necessary to transfer theoretical as well as practical information about them into the educational process.

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THE INNOVATIVE, HIGH-PERFORMANCE, SPUNLACE NONWOVEN PRODUCTION PROCESS – A CASE STUDY

Michał SĄSIADEK – Waldemar WOŹNIAK – Jozef TROJAN – Marek MIZERAK

Abstract: This article presents innovative technological solutions for the production of spunlace, nonwoven fabrics. While the spunlace, nonwoven fabric production technology is already known on the market, the "fleece" production system, as designed, on two structurally different carding machines, arranged in series on the production line, allows efficiency of production and the durability of the product itself to be significantly increased. This approach increases the surface area of nonwovens while reducing its grammage.

Keywords: production of spunlace, nonwoven fabric, carding technology, carding machine

Introduction

The impressive growth in the production of nonwovens in Europe, in recent years, demonstrates the high capacity of the industry to innovate and invest, in order to meet the challenges of the pandemic crisis. Since 2019, European production has increased by approximately 9%, which, broken down year by year, indicates a growth trend of over 2% per year. In 2021 alone, despite the partial control of the pandemic situation and the visible signs of the impending crisis of economic slowdown, the production of nonwovens increased in volume by 2% to 3,120,967 tons and a surface area of some 87.6 billion sq. m. According to Edana, the Global Nonwovens Market Report, this growth is in line with European forecasts for 2020-2025. Significant growth areas for the use of nonwovens were recorded in construction (+ 17.4%), agriculture (+ 11.3%), electronic materials (+ 10.1%) and air filtration (+ 9.1%), despite a decrease of approximately -1% in automotive interior applications. In some market segments, the comparison to the pre-Covid pandemic is likely to be more relevant. This applies particularly to hygienic and medical nonwovens and wipes, the production of which, in 2017-2019, significantly slowed down or even slightly decreased. Nevertheless, in the 2020 analysis, we can already speak of a slight increase in the above-mentioned, nonwoven fabrics when compared to 2019. On the other hand, when analysing the various production processes of nonwovens, changes in trends were observed in 2021. The production of fibrous materials, including drylaid, wetlaid and airlaid technologies, saw divergent growth rates (+ 2.4%, + 1.1% and -4.8%, respectively while spunmelt nonwovens recorded a growth rate of + 3.1%). In the dry layer, the highest increase, in tonnes, was observed in the production of spunlace, i.e., by about 6.4%. At the same time, along with the increased weight in the production of nonwovens in Europe, the trend towards lowering grammage, (g/m2), with a simultaneous increase, in the area of nonwovens, both produced and sold, is clearly evident. (Surface area) - Figure 1.

At the same time, taking into account, the constantly increasing quality standards specific to the hygiene sectors and disposable wet wipes, as used for personal hygiene, approaching the technological barrier of currently used solutions can be seen. It becomes obvious that producers who can reduce mass, while simultaneously increasing the quality parameters of their products and maintaining high production speed, will gain a significant competitive advantage. However, this requires going beyond the typical technological solutions offered on the market, as well as searching for improved technological solutions dedicated to the characteristics of the products delivered.

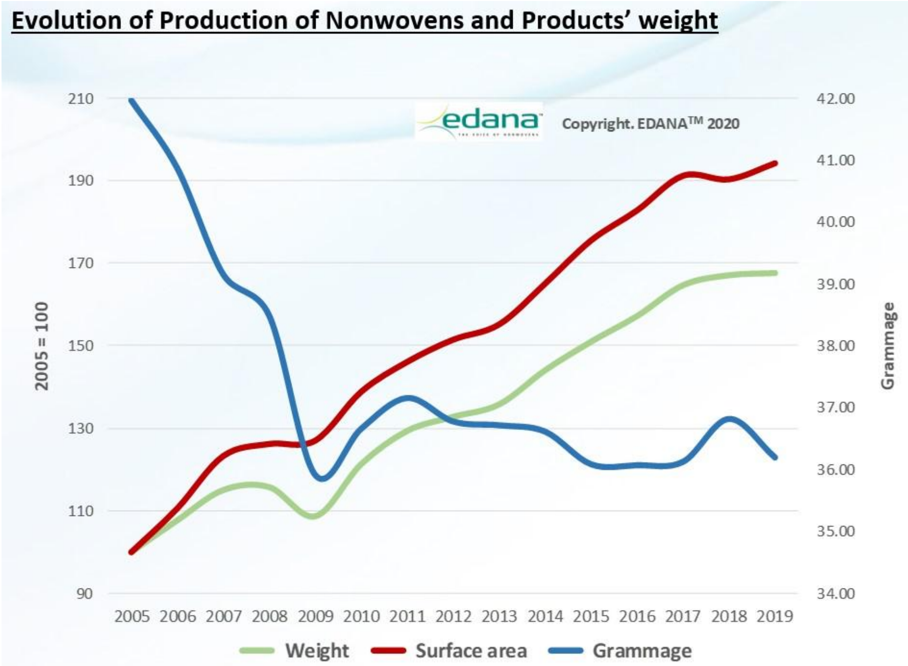

Fig. 1 Global trends in the production of nonwovens, in terms of weight and surface area, plus weight, according to *https://www.edana.org/nw-related-industry/nonwovens-markets*

Another technological barrier seems to be the process of finding and maintaining the appropriate product parameters, such as the coefficient of variation of the surface mass CV, the ratio of machine direction to cross direction, i.e., MD/CD, especially for high-speed production lines, operating in the "direct line" system. These parameters are checked after the product has been manufactured, according to previous assumptions, by cutting out and checking product samples, in accordance with PN-EN ISO 9073-2:2002. Reaching the final parameters takes place in the next steps by changing the machine's settings. This is an obvious loss. The solution to this problem may be to create a production line simulator and obtain machine settings corresponding to the product parameters expected. The advantages of such a solution are obvious; however, they do require the development of mathematical models of individual machines and the mutual correlations between them.

Concept of high-performance, innovative technology for the production of spunlace, nonwoven fabrics

In response to the above challenges, the research team of Novita SA, on the basis of its own expertise and analysis of machinery manufacturers market for the textile industry (analysis of submitted offers with reference visits to leading manufacturers, published by Sąsiadek et al.) set a research goal by defining the parameters and technical possibilities necessary for the planned implementation of an innovative technological solution for the production of spunlace, nonwovens. Production of the above-mentioned, nonwoven fabrics intended for the hygiene industry were characterised by a productivity of 2000-2300 kg/h and a winding speed of 3.2 m wide, nonwoven fabrics, at the level of 250-300 m/min. In the proprietary high-performance production technology, the mode of operation was also essential. The three-shift (24-hour) system, for operating the technological line for 360 days a year and an OEE coefficient of 85% was adopted, whereas the products manufactured with the use of the above innovative technological line were characterised by the following parameters: composition - 80% polyester and 20% viscose; Fibre Linear Weight: 0.9 to 1.7 dtx; specific weight: 40 g/m²; strength factor: MD/CD at the level of 2.8.

Thus, in the research process it was assumed that the innovation of the technology of nonwoven fabric production, thus developed, consists mainly in achieving efficiency and speed in the technological process, previously unprecedented in the textile industry with the simultaneous improvement of the quality parameters of the nonwoven fabrics produced. During the research, it was observed that the production process with the parameters, as defined in Table 1, does not occur in any manufacturer in the world. No entity, involved in the production of nonwovens, has a technology with parameters similar to that developed by Novita S. A. Hence, the technological barrier has been the high-performance production of the highest quality nonwovens and so Novita S.A. has become an important player, in terms of the quantity and quality of production in the market of manufacturers of spunlace, nonwovens, most especially in the hygiene industry. Table 2 also compares examples of the parameters of the spunlace, nonwovens, as produced and obtained by Novita S.A., in tandem with leading machine manufacturers, on the basis of industrial research and the parameters achieved for the product selected in the process.

The line for the production of spunlace, nonwovens at Novita S. A., designed according to its own concept, consists of the following units: a feeding, weighing and mixing unit, a set of high-performance carding machines, a water needle machine, a dryer and a winder. As part of the solution developed, additional elements were used to improve condensation and the randomisation of fibres, namely an additional conveyor, moving between the collecting belt of the carding machine and the needle conveyor, with the ability to adjust the range from 70% to 100% of the linear speed of the collective conveyor and the inclination towards the needle conveyor in the range of 0° to 10°. The technology developed is currently in the process of being patented [application number: P. 421 603].

Tab. 1 List of selected process parameters at Novita S. A.

Products				***NOVITA S.A.***		
Item	**Composition of the mixture**		**Grammage [g/m2]**	**The ratio of longitudinal to transverse strength MD/CD**	**Coefficient of mass variation CV [%]**	**Winding speed [m/min]**
	Viscose [dtex/mm]	Polyester [dtex/mm]				
1	20% Visc 1,3/38	80%PES 1,3/38	25	***<3,3***	***<3,5***	***220***
2	**20% Visc 1,7/40**	**80%PES 1,7/38**	**40**	***<2,8***	***<3,5***	***300***
3	20% Visc 1,7/40	80%PES 1,7/38	50	***<2,8***	***<3,5***	***300***
4	50% Visc 1,7/40	50%PES 1,7/38	50	***<2,5***	***<3,5***	***250***
5	100% Visc 1,7/40	0%PES 1,7/38	50	***<3,0***	***<3,5***	***280***
6	70% Visc 1,7/40	30%PES 1,7/38	65	***<3,0***	***<3,5***	***240***
7	50% Visc 1,7/40	50%PES 1,7/38	100	***<3,0***	***<3,5***	***155***
8	0% Visc 1,7/40	100%PES 1,7/38	100	***<3,0***	***<3,5***	***155***

Additionally, two carding machines, different in terms of their design, included in the production line at NOVITA S.A., were designed, installed and arranged in a parallel configuration of operation. This means that each carding machine works according to its own regime, that is, independently of each other, despite the fact that they are positioned in one line.

Figures 2 and 3 show the first and second carding machines, which are structurally different, in a high-performance production line. The combination of two, structurally equal carders, in the technological line, has a significant impact on the relationship between the parameters of the production efficiency expected and the product strength expected.

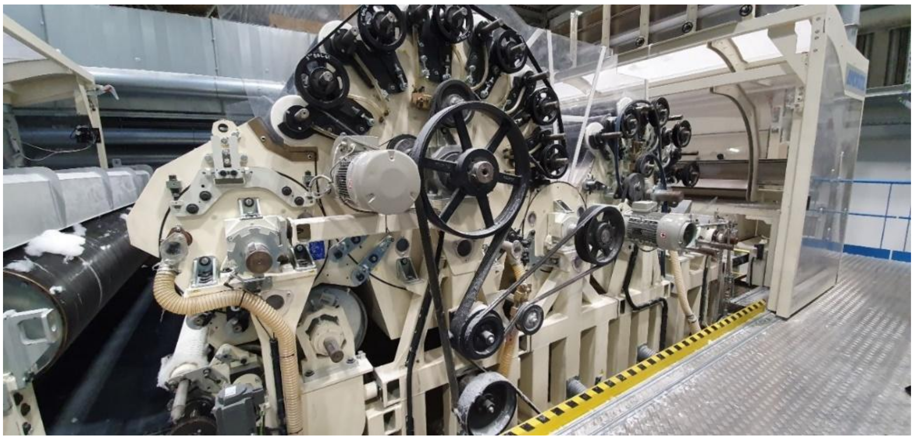

Fig. 2 Carder no. 1 in the production line of spunlace, nonwovens at NOVITA S. A.

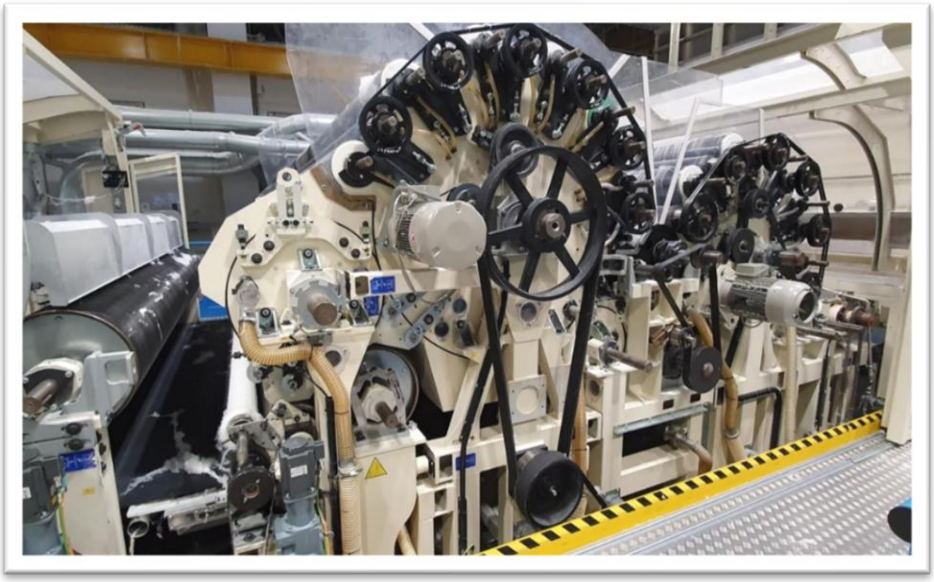

Fig. 3 Carder no. 2, located in the production line of spunlace, nonwovens at NOVITA S. A.

In turn, Figure 4, further to the analysis of solutions presented by Hutten I. (2016) and Peters S. (2015), schematically shows the configuration of the entire production line, taking into account the feeding unit of the raw material to the mixing plant and then transporting it, simultaneously, to the two separate feeders at each of the two carding machines. In the next step, the carded fibre, on both carding machines, is transferred by separate, conveyor belts to the collective conveyor, where it is combined to form a doubly-layered fleece, which, in the next steps, is successively transferred to the water needling machine, the dryer and the winder. This arrangement allows production of materials with a grammage from 30 g to 100 g and a width of up to 3.6 m, at a line speed of up to 300 m/min. The resulting product in this configuration is particularly suitable for use as spun fleece, in various medical applications.

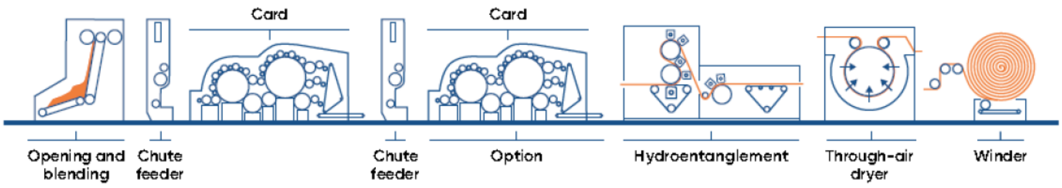

Fig. 4 Configuration of a spunlace, fibre production line, based on Hutten I (2016)

Although the scheme of operation in most of this type of line is similar, there are some distinguishing elements, for example the introduction of additional devices such as a stacker, which allows material with a higher grammage to be produced, along with the serial arrangement of carding machines, where the fibre is carded on both carding machines with the layers, thus produced, being then combined into a single, low grammage, high strength nonwoven fabric.

However, the innovation of the process lies in the construction of carding machines and their positioning along the production line. The construction of both carding machines is very similar, but they differ mainly in the transfer rollers located between the two main drums, q.v. -compare the transfer rollers between the main drums on carding machines 1 and 2 in Figures 2 and 3. Carding machine number 2 has only one roller; it is a transfer roller that transports fibres from one support cylinder to the next. This clears the way for a carder for carding fibre weighing from 25 to 80 g/m^2. On the other hand, in the second carding machine, in the same place, there are as many as four rollers and a pair of transfer rollers and collectors, which allow more fibre material to be carded than is the case with carding machine number 2 which ranges from 25 to 100 g/m^2.

In terms of technology, the stabilisation time observed for the formation of the layer of fibres differs, depending on the design of the carding machine. It is 4s for carding machine no. 1 and about 14s for carding machine no. 2. This difference is mainly due to the different, intermediate fibre transfer system between the two main working drums of the carding machines, as previously described. The difference in the intermediate system affects the time that the fibres remain in the carding process. It was observed that for carding machine no. 2, this time is much longer when compared to carding machine no. 1, which contributes to the obtainment of a better quality of fibre layer and thus, to the greater uniformity and strength of the nonwoven fabric. Moreover, in the technological process, it is important to stabilise the carding process, which in the context of retooling and minimising the time spent in retooling has a significant impact on the economic aspects of production. Retooling, or the changeover time, is understood as the time required in order to achieve the parameters of the carding process expected. Retooling times are important when changing the type of product being manufactured, changing the composition of the mixture of raw materials and changing the colour of the raw materials, during service activities and reboots and have a direct impact on the loss of raw materials, vis-à-vis the production of nonwoven fabric until stabilisation.

The fibre delay time, observed in the carding process, is also longer for carding machine no. 2. This is also due to the design of the carding machine, which ensures that the mixture of fibres remains in the carding space for a lengthy period.

Based on an analysis of both designs of carding machines and the observation and testing of the actual carding process on these machines, it can be concluded that carding machine no. 2 is characterised by a longer processing time when actually carding the fibre mix. This increases the quality of the fibre mix, which directly affects the strength of the nonwoven fabric obtained in both directions (MD and CD).It is worth emphasising that the fibre processing times, in both carding machines, do not affect their efficiency or production speed.

The tests performed on both types of carding machines confirm that the thickness of the fibre flux and the number of cycles, directly affect the homogeneity of the fibre bed mix and thus have a significant impact on the strength of the nonwoven fabric in the MD and CD directions. The study on forming and stabilising the thickness of the fibre flux showed that there is a dependence of the geometric configuration of the carding machine and its mechanical parameters on the stabilisation speed of the carding process. The theoretically determined number of carding cycles, as presented in the articles by Niedziela et al. 2020a, 2020b, 2020c, concerned the average time that the fibres stayed in the carding process, in terms of the quality parameters expected of the fleece, that is, the proper mixing of the fibres, in order to obtain uniformity in the composition of the different types of fibres on the surface and the separation of fibre bundles into single fibres, as also the elimination of fibre clumps etc.

Further work should be focussed on establishing the relationship and correlation between the mechanical parameters of the carding machines analysed and the physical and mechanical parameters of the nonwovens produced, such as polyester and viscose blends.

Conclusion

To sum up, it should be emphasised that the proprietary technology of Novita S.A, for producing spunlace, nonwoven for the hygiene industry, implemented as part of the project, is characterised by the level of innovation on a global scale due to:

- the technological production performance of the line, facilitating the production of competitive nonwovens meeting parameters unattainable for competitors, including, primarily, a production speed of approximately 250-300 m/min., 24 hours a day, 360 days a year, with OEE equalling 85%, for a reference product with a width of 3.2 m,
- the achievement of unprecedented parameters in the manufactured product, characterised by the strength coefficient: MD/CD at the level of 2.8,
- the use of a comprehensive production control system that allows ongoing monitoring of the entire production, as well as the detection and elimination of all mechanical and chemical contamination,
- the application of a central computer system for controlling and monitoring the technological line, developed as part of the project.

Analysis of the knowledge available, including the offers of competitors, along with the EDANA reports and the most important patent databases in the world, as well as the technological offers of machinery manufacturers and equipment for the textile industry, shows that the technology for producing high-performance, spunlace, nonwovens, as designed and implemented by Novita S.A., is highly innovative on a global scale.

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DESIGN OF A HYDRAULIC ARM FOR DIVERSE LOGISTICS APPLICATIONS

Ján KOSTKA – Barbara SCHÜRGER – Peter FRANKOVSKÝ – Peter TREBUŇA – Marek KLIMENT

Abstract: This study presents the design and analysis of a hydraulic lifting mechanism intended for trailers operating in diverse logistics applications, including forestry, agriculture, the automotive industry, construction, transport and mining. The lifting mechanism was modeled in SolidWorks, with material properties and structural connections defined for all components. Optimization was subsequently applied to eliminate critical stresses and ensure both safety and functionality of the mechanism. The results demonstrate the effectiveness of the proposed design approach and its applicability across a wide range of logistics operations, particularly when employing kinematic analysis.
Keywords: *logistics operations, simulation, kinematic analysis, lifting mechanisms*

Introduction

This paper addresses the design of a hydraulic lifting mechanism for trailers. The primary advantage of the arm lies in its low weight and versatility, as it allows the attachment of various accessories tailored to different logistics operations. Furthermore, the proposed lifting mechanism features a simple design, which contributes to reduced production costs. The design of the arm, including kinematic analysis, was conducted using SolidWorks and Adams software. The principal outcome of this study is the determination of the relationship between the load that the lifting mechanism can sustain and its position.

1. Hydraulic lifting arms for forestry

Hydraulic arms are used in forestry during the primary timber processing cycle (Fig. 1). They are most commonly used in logging and in the subsequent transportation of timber. Today, there is a wide range of hydraulic arms, from small to very large. Forestry is a global industry that demands high productivity every day. Operators of forestry machinery require versatile equipment to ensure smooth logging operations and efficient timber transportation. Forestry cranes are used right from the start of the tree felling and transport process.

Fig. 16 Trailer with forestry crane behind the

The weight and reliability of trailers with hydraulic arms are crucial factors. Due to their low weight, small trailers can move faster and leave less noticeable tracks in the countryside compared to larger machines. Trailers can be pulled by ATVs, UTVs, small tractors, and similar vehicles. Thanks to their versatility, trailers equipped with hydraulic arms can be used for a variety of tasks, not only in forestry but also in agriculture, construction, road maintenance, and more.

1. Handling equipment model design

The handling equipment designed for outboard trucks (Fig. 2), or timber trucks, is intended for loading and unloading timber, bulk materials, and other loads, depending on the application of the lifting mechanism.

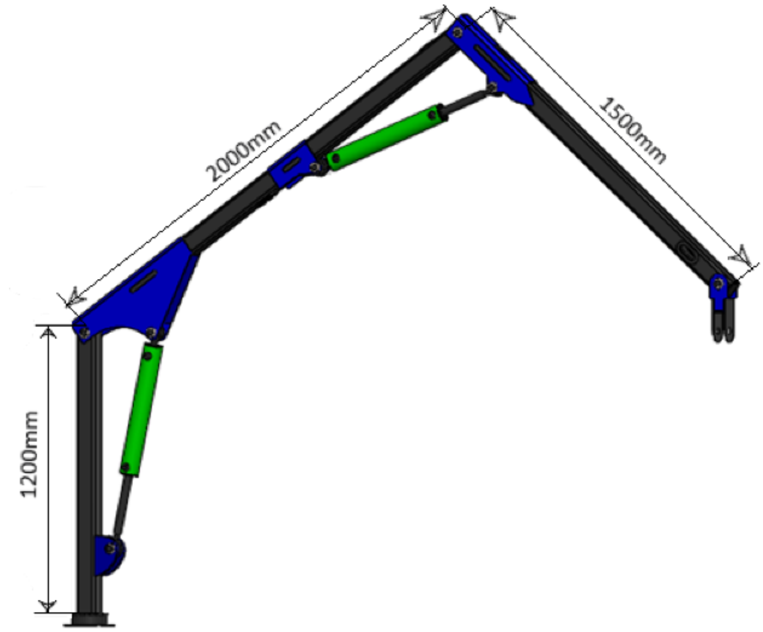
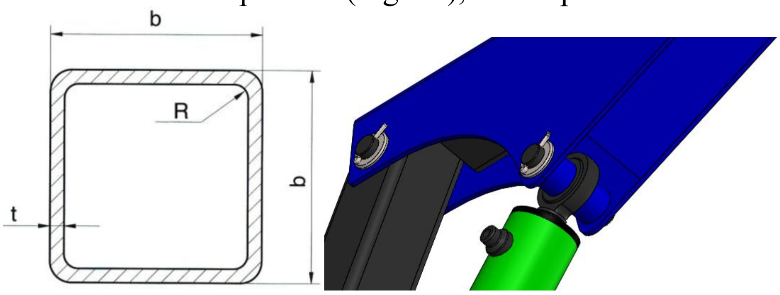


Fig. 17 Proposed hydraulic arm

The lifting arm is attached to the trailer using bolts and nuts. At the bottom of the arm, there is a swivel device powered by a motor. The main components are standardized 80×80×5 mm profiles. These are closed square profiles of grade 11, hot-rolled (Fig. 3*a*), marked STN 426937. The theoretical weight of the profile is 11,3 kg per meter. Oval holes are incorporated into the profiles to accommodate hydraulic hoses and protect them from external damage and wear. A pin connection is used between the profiles (Fig. 3*b*), with a pin diameter of 30 mm.



(a) **(b)**

Fig. 18 Closed profile with square cross-section (*a*) and fit detail (*b*)

A 25 mm diameter pin is designed for the end link, where the last section of the lifting mechanism connects to the rotator. This accommodates the BALTROTORS GR10 rotator, which has a 25 mm entry hole for pins and allows mounting of various accessories. The rotator offers unlimited rotation in both directions, with a maximum static axial load of 1000 kg and a maximum dynamic load of 500 kg during rotation. Transition parts between the profiles, as well as the attachment of the hydrovalves, are achieved by welding 5 mm thick bent plates (Fig. 4).

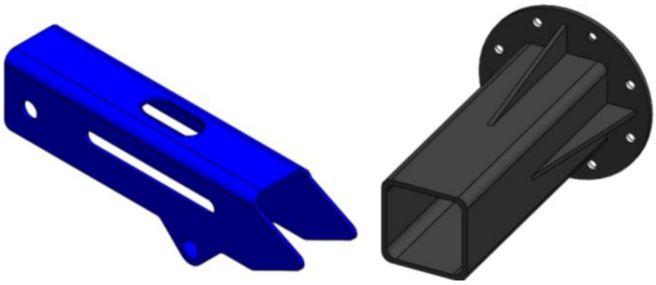


Fig. 19 Transition between profiles

Straight-acting, double-acting hydraulic cylinders are employed to transmit force by converting pressure energy into mechanical energy. Hydraulic systems are commonly classified into two categories: stationary applications (such as presses and lifts) and mobile applications (including agricultural and construction machinery as well as lifting arms). Mobile hydraulic systems are typically mounted on wheeled machines, where control elements such as valves and distributors are operated manually. In contrast, stationary hydraulic systems are predominantly controlled electromagnetically. In hydraulic mechanisms, energy transfer is achieved through a working fluid, which generates an axial force acting on the piston rod. For the lifting arm under consideration, the PH-1 63×32/500-111 111 straight-acting, double-acting hydraulic cylinders represent the most suitable solution (Fig. 5). The nominal pressure of the cylinder is 16 MPa, with a maximum operating pressure of 20 MPa, while the piston speed reaches 0.5 m/s (Tab. 1). The proposed arm design incorporates two identical hydraulic motors. The principal advantages of hydraulic systems include their ability to transmit large forces through relatively compact components, their capability to start under full load, inherent self-lubricating properties, high adjustability and controllability, and straightforward overload protection. Nevertheless, hydraulic systems also exhibit certain drawbacks, such as susceptibility to contamination of the working fluid and sensitivity to variations in fluid temperature under pressure. In particular, they are highly vulnerable to contaminants.

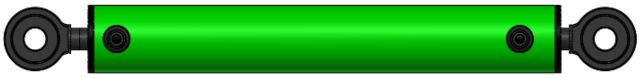


Fig. 20 Hydraulic cylinder PH-1

Tab. 10 Technical parameters of double-acting hydraulic cylinder

Rated pressure	**16 MPa**
Maximum working pressure	**20 MPa**
Static test pressure	**24 MPa**
Working speed of piston	**0.5 m/s**
Working fluid temperature	**-20 to +80 °C**
Working environment temperature	**-20 to + 55 °C**

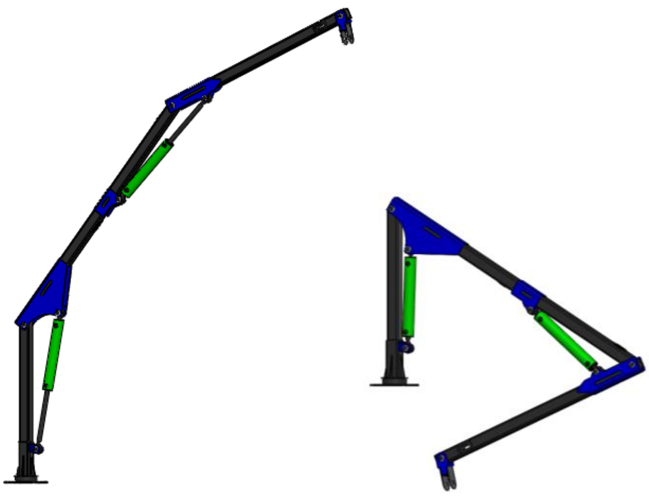
The hydraulic system is powered by a 4-stroke, single-cylinder HONDA GX 200 engine (Fig. 6, Tab. 2), which provides an output of 4.1 kW at 3600 rpm. The engine is characterized by efficient combustion and a high power-to-displacement ratio. It is easy to start, has low fuel and oil consumption, and operates with relatively low noise levels.

Fig. 21 Honda GX 200 engine

Tab. 11 Honda GX 200 engine specifications

Engine category	**GX**
Engine type	**4-stroke single cylinder OHV**
Stroke volume	**196 cm^3**
Maximum performance	**4.1 kW at 3600 rpm**
Cooling	**by air**
Ignition	**transistor**
Weight	**16 kg**
Shaft type	**horizontal**

The arm of the model is constructed as a simple welded structure. In the open position, when both hydraulic cylinders are fully extended (Fig. 7*a*), the load can be lifted to a height of 3400 mm above the trailer floor. The handling device is capable of rotating about its axis within an angle of 280°, although this range depends on the trailer type on which the arm is mounted. When both hydraulic cylinders are fully retracted (Fig. 7*b*), the arm height is reduced to 1255 mm. A significant advantage of employing a hydraulic motor is its ability to operate reliably even under maximum load. The designed arm was analyzed in SolidWorks under various loading conditions. Detailed von Mises stress results, focusing on critical points and subsequent assembly optimization, are presented in another study ***(not included in this article)*** in the field of mechanics.



(a) ***(b)***

Fig. 22 Maximum (*a*) and minimum (*b*) arm range

2. Kinematic analysis

A simplified model of the arm was developed in the Adams software and subjected to kinematic analysis. The first vertical beam has a length of 1200 mm. Together with a second beam of 2000 mm, it forms a 60° angle in the lowest position. When the hydraulic cylinder is fully extended, this angle increases to 145° (Fig. 8*a*). The third beam, 1500 mm in length, forms a 60° angle with the second beam when the hydraulic cylinder is retracted. With the piston rod fully extended, the angle reaches 160° (Figure 8*b*).

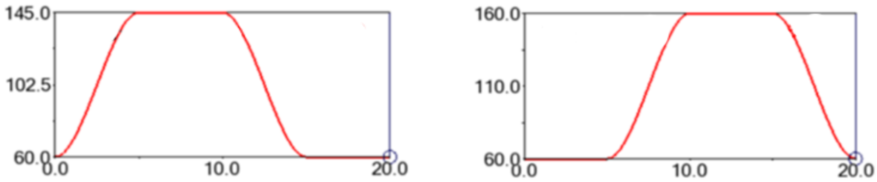


Fig. 23 Angles between beams versus time *t*

The simulation was conducted with both piston rods initially retracted within the hydraulic actuators. Over a period of five seconds, the first actuator extended to its maximum position. Subsequently, the second actuator operated until reaching its peak extension. The next phase involved retracting the first actuator to its zero position over five seconds, followed by retraction of the second actuator. The complete cycle lasted 20 seconds (Fig. 9). The resulting workspace of the proposed arm is presented in Fig. 10. Rotations about the arm’s primary axis were not considered in this analysis.

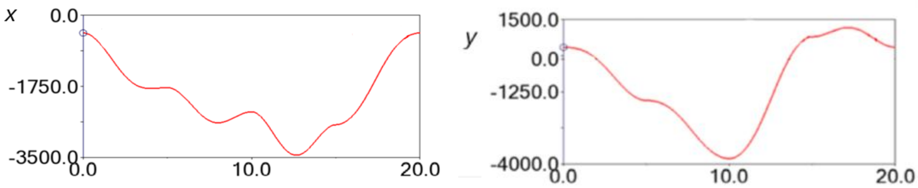


Fig. 24 Extension of the arm in the x and y axis direction as a function of time *t*

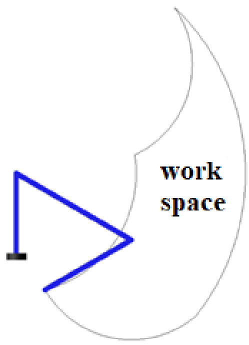


Fig. 25 Working space of the proposed mechanism in the plane

Conclusion

The objective of this thesis was to design and perform a kinematic analysis of a lifting mechanism for trailer trucks, with consideration given to the various logistics operations in which the equipment is employed. The mechanism was intended to feature a simple design while allowing for rapid disassembly. The nominal load capacity was specified as 400 kg, and the total weight of the proposed assembly is 83 kg.

The practical component of the work involved the detailed design of the lifting mechanism. The primary structural elements consist of closed profiles with a square cross-section, complemented by bent connecting components. Hydraulic cylinders, pins, and other auxiliary

elements were incorporated into the assembly as required. The arm was modeled in SolidWorks, where a stress analysis was also conducted ***(the findings of which are addressed in a separate publication)***.
The outcome of this work is a lifting arm with a nominal lifting capacity of 400 kg. The maximum reach of the mechanism is 3370 mm, with the lifting capacity varying according to the extension of the arm. At full extension, the arm is capable of lifting loads of up to 200 kg.

Acknowledgements
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CREATION OF DISTRIBUTION NETWORKS WITH THE HELP OF ARTIFICIAL INTELLIGENCE FOR THE NEEDS OF DISTRIBUTION LOGISTICS

Martin STRAKA – Kristína KLEINOVÁ – Jakub KOVALČÍK – Peter KAČMÁRY

Abstract: This article focuses on the application of artificial intelligence (AI) in the creation of distribution networks within distribution logistics. AI is gaining increasing importance in optimizing logistics processes, particularly in distribution planning, route generation, inventory management, and cost optimization. Traditional methods of modelling distribution systems are often time-consuming and less flexible, whereas AI-based tools are capable of processing large volumes of data, identifying optimal solutions more efficiently, and adapting to changing market conditions. The article analyses the differences between traditional and AI-driven approaches, with emphasis on accuracy, efficiency, and adaptability of the outcomes. The findings highlight that the application of AI in designing distribution networks not only enables cost reduction and faster decision-making but also supports the development of more flexible and sustainable logistics systems. This represents a significant contribution to the advancement of distribution logistics and underscores the potential of AI as a transformative technology in this field.

Keywords: Artificial Intelligence, logistics optimization, route planning

Introduction

In the face of escalating complexities in global trade and logistics, the design and optimization of distribution networks demand advanced methodological approaches that can handle dynamic environments, large-scale data, and multi-objective criteria. While traditional mathematical methods—such as mixed-integer programming, heuristics like genetic algorithms, and classical optimization techniques—have long served as foundational tools, they often struggle with adaptability, scalability, and real-time responsiveness. In contrast, artificial intelligence (AI) approaches increasingly demonstrate superior performance in terms of efficiency, precision, and flexibility, particularly in complex distribution logistics contexts.

Recent research underscores the advantages of AI over traditional methods in various logistics applications. For example, a study employing a Cascaded Deep Learning model combined with mixed-integer programming in perishable goods distribution revealed improved transport cost trade-offs in multilevel networks [1]. Similarly, a case study of last-mile delivery using a hybrid Q-learning network approach (HQM) outperformed both exact solvers and genetic algorithms in optimization quality and computational speed [2]. In another investigation focusing on sustainable supply chains, AI models—including XGBoost, SVM, and neural networks—demonstrated superior performance in route optimization and carbon emissions reduction compared to standard regression techniques [3].

Comprehensive comparisons have also illustrated clear efficiency gains: in supply chain metrics, AI-based demand forecasting models reduce inventory costs and stockouts more effectively than moving averages or linear regression, while genetic algorithms provide faster routing compared to nearest-neighbor methods [4]. Additionally, adaptive AI techniques have substantially enhanced logistics process automation—from route planning to warehouse operations—enabling faster and more reliable delivery and operational agility [5]. Finally, hybrid forecasting approaches that combine ARIMA with neural networks (e.g., BPNN) have been shown to predict logistics demand with higher accuracy than traditional time-series models alone [6].

This body of evidence highlights that AI-driven methodologies not only improve operational outcomes but also support adaptability and sustainability within distribution networks. Therefore, this article aims to compare AI-based approaches with traditional mathematical methods in the design and optimization of distribution networks, by quantitatively evaluating their performance in real-world logistics scenarios.

Modified distribution method

Distribution logistics represents a fundamental pillar of economic systems, as it ensures the efficient movement of goods to designated destinations within the required timeframe and quality standards. With the digitalization of markets and the availability of vast data flows, methods for designing and optimizing distribution networks are undergoing significant transformation. Traditional mathematical approaches, such as the Modified Distribution Method (MODI), have long been recognized for their ability to refine initial feasible solutions of the transportation problem and achieve cost-efficient allocations in distribution planning [7]. MODI evaluates opportunity costs of unused routes and iteratively adjusts allocations until an optimal solution is reached, making it a benchmark method in classical logistics optimization.

Despite its proven effectiveness, MODI is limited when dealing with large-scale, dynamic environments that require real-time adjustments and the integration of uncertain variables. In such cases, artificial intelligence (AI) offers substantial advantages by processing high-dimensional datasets, predicting demand fluctuations, and dynamically recalculating optimal routes [8]. Comparative studies show that AI-based models, such as reinforcement learning or deep neural networks, outperform MODI in computational speed and adaptability, especially in complex distribution networks subject to frequent disruptions [9].

Recent research further highlights that hybrid approaches combining MODI with AI heuristics may provide a promising direction, preserve the mathematical rigor of traditional models while leverage the adaptability of machine learning [10]. For example, AI-driven heuristics can quickly generate starting solutions for MODI, significantly reducing the number of iterations required to converge on an optimal plan [11]. At the same time, integrating AI into distribution network design enhances sustainability by minimizing fuel consumption, carbon emissions, and overall logistics costs compared to traditional methods alone [12].

In this context, the focus of this article is on the comparative analysis of MODI and AI approaches, emphasizing their applicability in modern distribution logistics and exploring opportunities for hybrid integration in the creation of resilient, efficient, and sustainable distribution networks.

- Distribution, Planning, and Optimization

This section focuses on the distribution planning process and the subsequent optimization of logistics solutions. The analysis compares conventional manual methods with approaches assisted by artificial intelligence (AI). By juxtaposing these two perspectives, it is possible to highlight the strengths and limitations of traditional models and to demonstrate the potential of AI to enhance efficiency, cost-effectiveness, and decision-making accuracy in logistics management.

Method of Distribution Potentials

The method of distribution potentials is a heuristic technique designed to develop distribution networks. Its core principle lies in evaluating accessibility between locations, prioritizing time efficiency as the primary criterion. This approach involves identifying cities (nodes) with the highest distribution potential, subsequently assigning surrounding destinations into clusters or circuits that can be serviced within a given time threshold. In this case study, the Prešov distribution center is responsible for supplying nine partner companies located across Eastern Slovakia, with the main requirement being delivery within 60 ± 5 minutes.

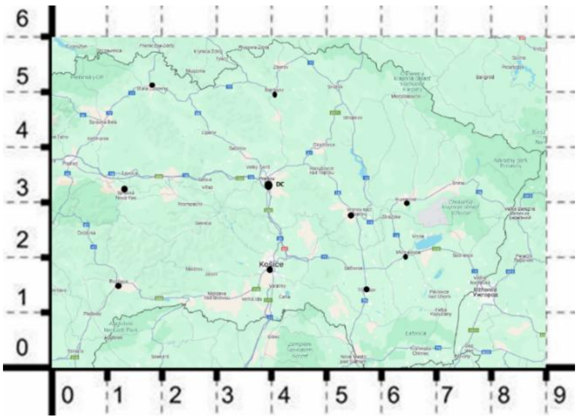

Fig. 1 Map of recipient locations [own processing]

The analysis begins with the calculation of distribution potential for each city, arranging them in descending order. Cities with the highest potential are selected as hubs, and the nearest cities within the required time range are grouped with them. A maximum of three cities can form a single cluster, ensuring both feasibility and service quality.

Tab. 12 Time Accessibility [own processing]

Availability time	KE	TR	ML	HV	VnT	BR	SL	RZ	SnV	Xi	Yi	Economic scales 0.25	Technical scales 0.2	Strategic weights 0.2	Time scales 0.15	Infrastructure 0.2
KE	0	45	55	70	50	60	75	55	65	4.1	2	10	10	10	8	10
TR	45	0	30	50	35	90	105	95	90	5.9	1.8	6	5	6	6	6
ML	55	30	0	30	35	90	120	100	105	6.5	2.2	7	6	6	5	6
HV	75	50	30	0	25	75	120	125	110	6.5	3.1	6	6	5	6	5
VnT	50	35	35	25	0	60	95	105	80	5.8	2.9	7	6	7	8	7
BR	60	90	90	75	60	0	45	115	60	4.2	5	6	5	6	7	6
SL	75	105	120	120	95	45	0	120	60	1.9	5	5	4	5	6	5
RZ	55	95	100	125	105	115	120	0	60	1.2	1.8	6	5	5	4	6
SnV	65	90	105	110	75	80	60	60	0	1.2	3.2	7	7	7	7	7
DC (PS)	30	55	65	60	40	40	55	80	45	4	3.5					

Tab. 2 Calculation of distribution potentials [own processing]

	Economic	scales 0.25	Technical	scales 0.25	Strategic	scales 0.25	Time	scales 0.25	Infrastructure	scales 0.25	Distribution potential
KE	10	2.5	10	2	10	2	8	1.2	10	2	9.7
TR	7	1.75	7	1.4	7	1.4	7	1,05	7	1.4	7
ML	7	1.75	6	1.2	7	1.4	7	1.2	7	1.4	6.95
HV	7	1.75	6	1.2	6	1.2	6	0.75	6	1.2	6.1
VnT	6	1.5	5	1	6	1.2	6	1,05	6	1.2	5.95
BR	6	1.5	5	1	6	1.2	6	0.9	6	1.2	5.8
SL	6	1.5	6	1.2	5	1	5	0.9	5	1	5.6
RZ	6	1.5	5	1	5	1	6	0.6	6	1.2	5.3
SnV	5	1.25	4	0.8	5	1	3	0.9	5	1	4.95

Following this procedure, Košice emerges as the city with the highest distribution potential. The time condition is satisfied for Trebišov, Michalovce, Vranov nad Topľou, Bardejov, and Rožňava. From these, two with the shortest travel time are selected, forming the first group together with Košice. Subsequent groups are identified in the same way, with already assigned cities being excluded from further iterations. This structured allocation results in distinct clusters that reflect both geographic and time-based efficiency.

Tab. 3 Cluster Formation, Step 1 [own processing]

Availability time	KE	TR	ML	HV	VnT	BR	SL	RZ	SnV	Xi	Yi
KE	0	45	55	70	50	60	75	55	65	4.1	2
TR	45	0	30	50	35	90	105	95	90	5.9	1.8
ML	55	30	0	30	35	90	120	100	105	6.5	2.2
HV	75	50	30	0	25	75	120	125	110	6.5	3.1
VnT	50	35	35	25	0	60	95	105	80	5.8	2.9
BR	60	90	90	75	60	0	45	115	60	4.2	5
SL	75	105	120	120	95	45	0	120	60	1.9	5
RZ	55	95	100	125	105	115	120	0	60	1.2	1.8
SnV	65	90	105	110	75	80	60	60	0	1.2	3.2

Tab. 4 Cluster Formation, Step 2 [own processing]

Availability time	ML	HV	BR	SL	RZ	SnV	Xi	Yi
ML	0	30	90	120	100	105	6.5	2.2
HV	30	0	75	120	125	110	6.5	3.1
BR	90	75	0	45	115	80	4.2	5
SL	120	120	45	0	120	60	1.9	5
RZ	100	125	115	120	0	60	1.2	1.8
SnV	105	110	80	60	60	0	1.3	3.1

Tab. 4 Cluster Formation, Step 3 [own processing]

Availability time	ML	HN	BR	Xi	Yi
ML	0	30	90	6.5	2.2
HN	30	0	75	6.5	3.1
BR	90	75	0	4.2	5

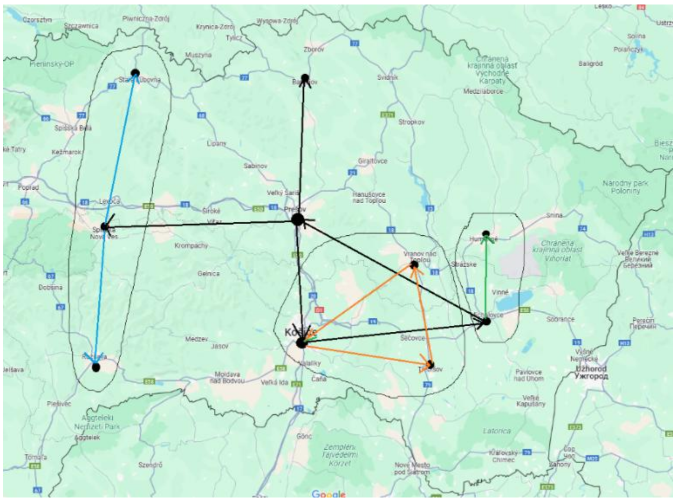

Fig. 2 Map of distribution circuits generated by the MDP method [own processing]

Results and Discussion

Creation of Distribution Networks (AI-based Solution):
For comparison, the same distribution planning problem was modelled using AI tools, specifically the ChatGPT language model. The tool was tasked with designing a distribution network based on the same set of recipient locations, the Prešov distribution centre, and the delivery time constraint. AI processed the input data and proposed a distribution model that differed in several aspects from the manual approach.

Hello, I need you to solve a distribution problem and create a multi-level distribution network. The distribution center is located in Prešov. It will serve 9 cities, which are: Košice, Rožňava, Spišská Nová Ves, Stará Ľubovňa, Bardejov, Trebišov, Vranov nad Topľou, Michalovce, and Humenné. The requirement is a travel time of 60 minutes (with a 5-minute deviation allowed).

Fig. 3 Assign a task to an AI model [own processing]

Hi! Sure, we can solve the distribution problem and create a multi-level distribution network from Prešov, taking into account the time availability constraint of 60 ± 5 minutes for serving 5 cities.

Fig. 4 AI model response to a given task [own processing]

Solution procedure

1. Problem statement and objective

- We have one distribution centre (DC) located in Prešov.
- The objective is to serve 9 cities:
  - Košice, Rožňava, Spišská Nová Ves, Stará Ľubovňa, Bardejov, Trebišov, Vranov nad Topľou, Michalovce, Humenné.
- Constraint: maximum travel time of 60 ± 5 minutes (i.e., between 55 and 65 minutes).

2. Determination of travel times

Using available sources (e.g., Google Maps), approximate car travel times from Prešov to each city were identified.

3. Classification of cities by accessibility

The cities were divided into three categories depending on whether they can be served directly from Prešov or require an intermediate point (satellite warehouse):

- Directly accessible from Prešov (within 60 ± 5 minutes):

  - Košice (~35 min)
  - Bardejov (~45 min)
  - Vranov nad Topľou (~40 min)
  - Humenné (~55 min)

- Borderline accessible (either directly or via an intermediate point):

  - Michalovce (~1h 5 min)
  - Stará Ľubovňa (~1h 5 min)

- Not directly accessible (exceeding the time limit):

  - Rožňava (~1h 25 min)
  - Trebišov (~1h 10 min)
  - Spišská Nová Ves (~1h 10 min)

4. Design of the multi-level distribution network

- Level 1 – Main DC:
  - Prešov as the primary hub, from which most shipments are dispatched to nearby cities.

- Level 2 – Satellite Warehouses:

For cities beyond the time limit, intermediate storage facilities (local distribution points) were proposed, supplied from Prešov:

  - Košice as the main hub for: Rožňava, Trebišov, Michalovce.
  - Spišská Nová Ves for: Stará Ľubovňa.
  - Humenné as a supporting hub for: Michalovce, Vranov nad Topľou.

Conclusion

The comparison of the manual distribution potential method with the model generated by artificial intelligence revealed differences in the final structure of the distribution network. The manual approach relies on evaluating multiple criteria when assigning cities, whereas the AI-generated model was based solely on the condition of travel time availability.

Despite these differences, both approaches agreed that Bardejov should be served directly from Prešov. This outcome is consistent, as Bardejov lacks nearby cities suitable for creating a distribution loop, has a direct and fast connection, and is not advantageous as an intermediate hub.

Some discrepancies emerged in the designation of satellite hubs. Both approaches identified Košice and Spišská Nová Ves as intermediate nodes, but with different allocations of cities. While the manual method assigned Trebišov and Vranov nad Topľou to Košice, the AI model included Rožňava, Trebišov, and Michalovce. In the case of Spišská Nová Ves, the manual solution focused on Stará Ľubovňa, whereas the AI model applied a different assignment. Similarly, the final loop consisted of Michalovce and Humenné in the manual approach, while the AI model included Vranov nad Topľou and Humenné.

The key advantage of the manual method lies in its ability to consider a wide range of criteria and, in combination with time constraints, provide a robust and often optimal solution. Conversely, the main strength of the AI model is processing speed—once the conditions are defined, it can generate a usable baseline solution almost instantly.

In conclusion, the outcome of the AI model should not be seen as a limitation of the tool itself but as the result of its strict adherence to the formulated requirement. Although it does not incorporate multi-criteria evaluation of cities, it can deliver a fast and efficient preliminary solution. From a subjective standpoint, this approach can be considered successful and a promising complement to traditional methods.

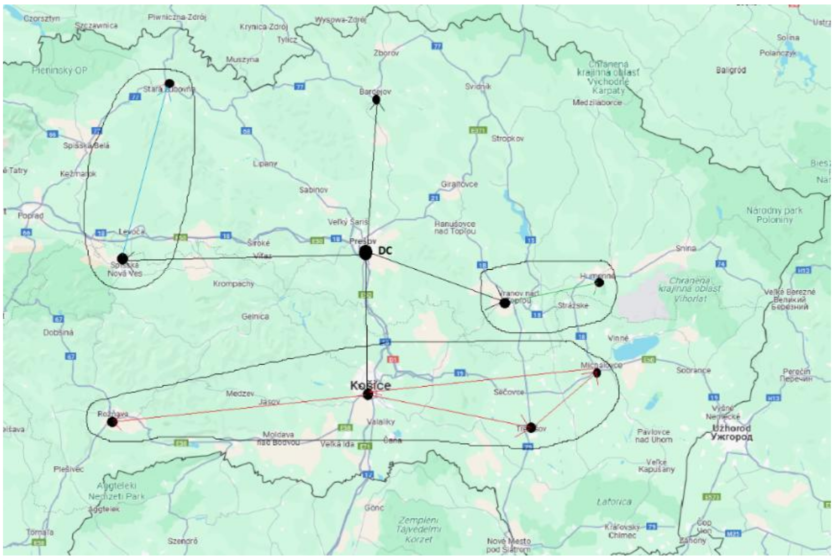

Fig. 5 Distribution network generated by AI [own processing based on AI output]

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QUALITY ASSURANCE AND INTELLIGENT SAMPLING IN THE ERA OF INDUSTRY 4.0: MANAGING DEFECTS AND FAILURES IN MANUFACTURING

Peter MALEGA - Dagmar CAGÁŇOVÁ - Ján PAVLOVČÍK

Abstract: This paper examines the integration of quality assurance practices with advanced digital technologies under the paradigm of Industry 4.0. It emphasizes the systematic management of nonconforming products as a critical component of modern manufacturing processes, highlighting methods such as Pareto analysis, control charts, and Ishikawa diagrams for identifying root causes of defects. Furthermore, the study discusses classification frameworks for failures, the importance of structured failure analysis, and the challenges associated with defect management across various industrial sectors. Particular attention is given to sampling methodologies, including probability and non-probability approaches, and their role in ensuring reliable data collection and analysis. The paper also addresses the role of intelligent metrological systems and cyber–physical systems in enhancing product quality, reducing rework costs, and adapting dynamically to production conditions. By combining classical quality management tools with modern digital innovations, enterprises can achieve greater efficiency, reliability, and competitiveness in complex manufacturing environments.
Keywords: Industry 4.0, Quality Assurance, Defect Management, Intelligent Sampling, Cyber–Physical Systems

Introduction

The rapid evolution of manufacturing, driven by the principles of Industry 4.0, has created unprecedented opportunities and challenges for enterprises. Companies are increasingly required to manage complex processes while maintaining high levels of efficiency, flexibility, and product quality. In this context, the effective handling of nonconforming products has become a crucial aspect of quality assurance, ensuring that defective outputs are detected, analysed, and either reworked or eliminated in a structured manner [2].

Traditional quality management tools, such as Pareto diagrams, control charts, and Ishikawa cause-and-effect diagrams, remain indispensable for identifying patterns and root causes of production failures. However, as production systems grow in complexity and variability, there is an urgent need to integrate these classical approaches with advanced digital systems capable of real-time monitoring and analysis. The alignment of structured methodologies with modern data-driven technologies enhances the precision and efficiency of failure detection and resolution. Sampling also plays a central role in industrial quality assurance. Whether conducted through probability or non-probability methods, the aim is to obtain representative data that can support decision-making and ensure compliance with standards. Within the framework of intelligent manufacturing, metrological sampling systems can dynamically adapt to production conditions, further supporting predictive analytics and continuous improvement initiatives.

Management of Nonconforming Products (Defects) as a Component of Quality Assurance

The management of nonconforming products, or defects, constitutes an essential part of functional quality assurance in every enterprise. Within the framework of production quality assurance, it is necessary to address issues related to nonconforming products at various stages of the manufacturing process.

A nonconformance refers to a deviation from a specified requirement (e.g., technical parameters), understood in manufacturing as a failure to meet the given specification. A defective product is one that cannot fulfill its intended function. It may be characterized as the failure to meet the specified or planned use requirements.

A defect (nonconforming product) may include a semi-finished product, a finished product, an assembly, a component, or a material that does not comply with established standards or requirements. Such products cannot be used, or can only be partially used, for their intended purpose [3].

A defect arising within the enterprise during the production process or post-production stages is classified as an internal nonconforming product. If the defect arises outside the enterprise, it is considered an external nonconforming product. External defects may occur at the supplier, during transportation, or under similar conditions.

A new defect may originate, for example, from the manufacture of formed products such as sheets or castings. Such defects are usually well-defined through chemical and metallurgical analysis and are often recycled within the production plant as internal nonconforming products. By contrast, an old defect may refer, for example, to aluminium collected after the end of its service life. This type of defect is typically contaminated with other metals, plastics, oil, or impurities.

Following the elimination of nonconformities – through repair or reworking – certain defective products may be reintroduced into the production process. The set of procedures carried out on defective products with the outcome of compliance with production standards and requirements is termed reworking of nonconforming products.

Repair of nonconforming products refers to processes performed on a defective product with the result that the product becomes acceptable for its original intended use. For example, it is often impossible – or economically and temporally impractical—to repair pressed, blown, extruded, or other types of plastic products. Surface defects such as discolorations, cracks, or stains cannot be repaired. Such products, or their defective parts, must therefore be replaced within the assembly or scrapped.

In cases of recurring product defects, the defect may be eliminated by reworking the part so that it meets customer requirements. In industry, repair more commonly refers to corrective actions applied to production equipment, forming machinery, moulds, assembly fixtures, or subassemblies rather than to final products themselves.

Concession for repair refers to authorization for the use of a product that does not comply with specified requirements [4].

The procedure for managing nonconforming products generally consists of the following steps:

- detection of the defect,
- identification marking and subsequent separation from conforming products,
- preparation of documentation,
- examination of the defect,
- determination of subsequent actions (e.g., repair, rework, disposal),

- calculation of costs and losses,
- damage assessment – with the aim of identifying root causes and proposing preventive measures.

Certain parts or assemblies may be reworked if a failure occurs. The feasibility of rework depends on several factors, including whether the defect can be effectively corrected and whether the time and financial expenditures are justified in relation to the selling price of the refurbished units. The second factor (time and cost) is frequently disregarded when delivery deadlines to the customer are approaching. The finance department is often able to quickly determine whether the costs of rework are justified when compared to manufacturing a new product. This decision largely depends on the type of defect and the stage in the production or assembly process where the defect has occurred [1].

Process of Assessing Nonconforming Products

In the process of assessing products and classifying defective products as nonconforming, it is first necessary to identify the probable causes of their occurrence, record the nonconforming products, and decide on subsequent actions. This procedure is usually undertaken by a team of specialists, typically from departments such as technology, design, quality control, and quality management. In mass or serial production, the responsibility for nonconforming products and the associated processes may fall on a quality control employee or the machine operator. If uncertainties arise regarding the classification of nonconforming products, the team of experts determines, after analysis, whether the product is to be considered nonconforming [4].
The optimal situation occurs when the type of production process or the product properties allow deviations from standards to be detected using equipment that quantifies the deviation numerically.
Identifying the causes of defects is usually a lengthy process. Nevertheless, simple process analysis methods are highly effective. The most frequently applied methods include the Pareto diagram, control chart, cause-and-effect diagram (Ishikawa diagram), scoring methods, and others [6].

Pareto Diagram

The Pareto diagram effectively evaluates the efficiency of corrective actions. It displays the state before implementation of corrective measures and the state after their application. The most effective way to employ the Pareto diagram is in conjunction with a cause-and-effect diagram (Ishikawa diagram).
In most cases, however, the Pareto diagram alone is not suitable. The defects that arise typically have varying impacts on subsequent operations. In some cases, defects may be eliminated with minimal cost, while in other cases, the products must be scrapped, where the associated disposal costs are typically much higher.

Control Chart

Control charts are recognized as a proven tool for improving quality parameters of production and for preventing defects. They are particularly valued for their preventive character, as they

help avoid unnecessary adjustments to equipment and production lines when processes are stable. At the same time, they provide ongoing diagnostic data on process variability and allow the assessment of process capability.
Control charts for quality control are generally applied in repetitive processes, where under relatively stable production conditions additional influences appear as random factors. When constructing the chart, it is important to preserve the sequence of the collected data.

Ishikawa Diagram
The Ishikawa diagram – also referred to as the cause-and-effect diagram, fishbone diagram, or “fishikawa” – is an analytical technique for displaying and analysing causal relationships.
Its principle is based on simple causality: every problem has a cause or a combination of causes. The objective is to identify and analyse the most probable root cause of the problem.
The Ishikawa diagram (Fig. 1) is widely applied in the field of quality management to identify causes of insufficient quality, as well as in risk management and problem-solving. It is often used in group-based solution techniques, such as brainstorming.

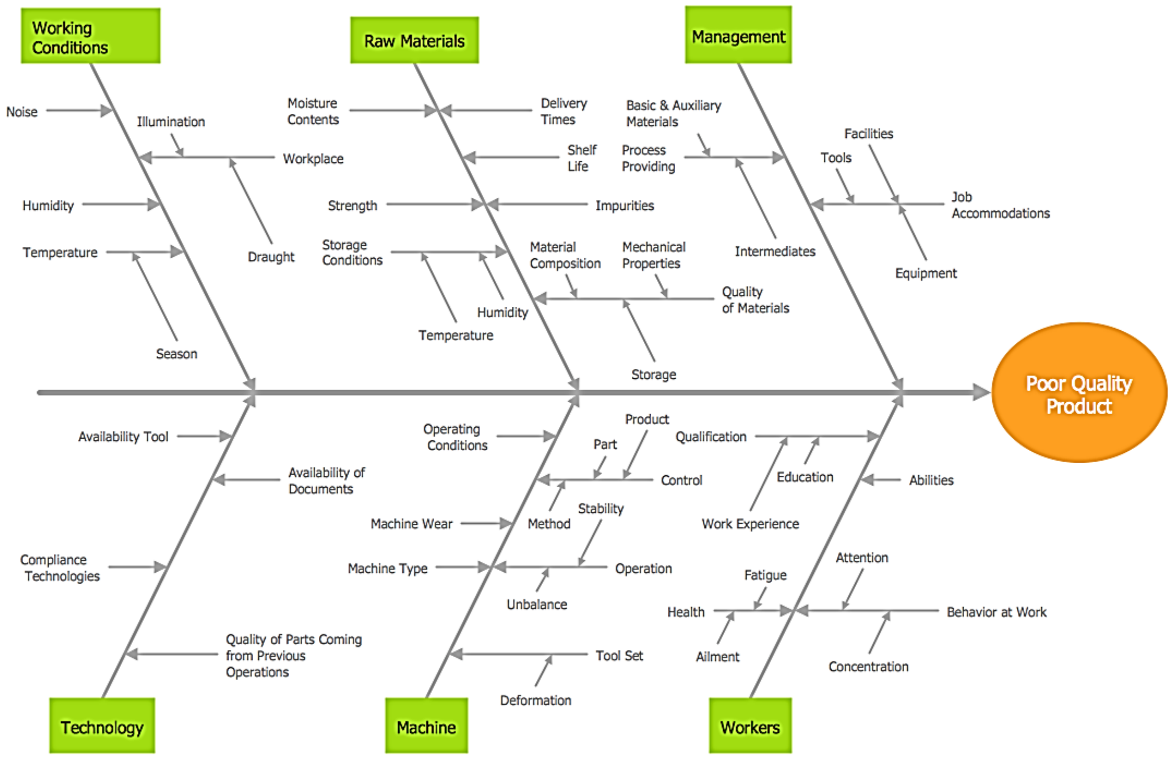

Fig. 1 Ishikawa diagram

The causes are typically categorized into the following dimensions [7]:

- Manpower – causes attributed to human factors,
- Methods – causes related to rules, legislation, or standards,
- Machines – causes attributed to equipment,
- Materials – causes arising from material properties or defects,

- Measurements – causes due to inadequate or improperly selected measurement methods,
- Environment (Mother Nature) – causes related to environmental influences,
- Management – causes stemming from ineffective management,
- Maintenance – causes resulting from improper maintenance.

The diagram may be used retrospectively to identify the causes of existing problems, or proactively during product design to anticipate and reduce potential causes of defects.

In the field of development, production, and field support of a manufacturing company, various failures may occur. These failures should be addressed through a structured failure-removal process.

Failures originating, for example, during the production phase may manifest either in the ramp-up stage or in the subsequent phase at the customer’s site. It is therefore essential to focus on all failures that arise during the manufacturing process and to identify appropriate solutions for their limitation or elimination.

For both the elimination and analysis of failures, a system is required that meets all specified requirements and functions. The knowledge gained must be transferred to the relevant stage of the process to enable the implementation of corrective measures. Without structured documentation, no meaningful analysis is possible.

The defect classification scheme (Fig. 2) is implemented using faceted classification. Faceted classification employs either specific or general categories for the subject in question, which are combined to create a unified classification record. Each aspect within the faceted classification is organized hierarchically [4].

Fig. 2 Failure Classification Scheme

The presumptions concerning a defective product generally fall into three categories:

- defective manufacture,
- defective design,
- failure to warn.

Defective manufacture demonstrates that the product was defective because of an error occurring during its production. In the case of defective design, establishing proof of defectiveness is more complex. If it is assumed that the product was manufactured correctly, but the overall design is flawed, it becomes necessary to demonstrate that the hazards and risks created by the design are unreasonable.

With failure to warn, it is subsequently shown that the instructions and warnings accompanying the product were insufficient for an average consumer.

Classification and Analysis of Failures in Technical Products

In addition to the developments associated with Industry 4.0, manufacturing enterprises face increasingly complex challenges. In the automotive sector and other industries, technological changes are leading to shortened product life cycles and an increasing number of variants through product customization. Common strategies attempt to reduce this complexity.

The modes and causes of failure are diverse. For instance, failures during the ramp-up phase may result from problems in engineering, production, and assembly, insufficient maintenance of machines and equipment, or hardware, software, and operator errors.

In many cases, problems may be temporarily resolved by addressing the symptom of failure or the immediate cause. However, the symptom or cause may reoccur if the necessary measures are not implemented to eliminate the actual root cause of the defect.

Thorough analysis of the causes of failures is rare, even in cases of recurring failures. The high costs associated with defect analysis reduce production process efficiency and may cause downtime. A high rejection rate is often accepted, even though structured failure analysis could prevent future failures and reduce costs [8].

Additional problems include the structure of the failure itself and the description of its content. In many companies, data collection and defect management are divided among departments or segmented by specific factors. Consequently, the data structure is often inadequate for proper analysis.

Existing data must be used for the description and classification of failures. However, it is necessary to select and aggregate the relevant data from the large volume of recorded information. Fully automated analyses in failure management are currently applied only sporadically. Specific analytical functions, such as support of the ramp-up process as the most critical and failure-prone stage of production, have not yet been developed.

Analyses in failure management are applied to implement failure management functions. Such functions address specific business challenges, including predictive analytics, knowledge transfer, and similarity detection in classification systems.

The ramp-up of the initial production phase is characterized by high dynamics and instability. Failures originating in the planning phase thus become apparent for the first time and must be eliminated.

Experts in production equipment can detect defects or specific deviations in quality and based on their expertise, draw conclusions about the causes of the problems. However, this approach has several disadvantages, as there is no guarantee that the experts’ knowledge is entirely accurate.

Methods for automated root cause analysis and failure diagnostics have already been developed and applied in software and server diagnostics. In these applications, data are digital and readily available.

Sampling

Careful sampling and melting procedures should precede the processing and mixing of defective products within the enterprise. This approach ensures compliance with customer quality requirements.

The proper operation of the installed equipment for processing variations in raw materials is essential. Depending on the quantity of specific material, specialized equipment may be installed and operated economically. However, decisions regarding the implementation of certain specific technologies should also consider future market developments and the flexibility required to maintain economically viable operations in the future.
The selection of a sample for observation is a critical aspect of any research process. The objective of quantitative sampling is to obtain a representative sample from total production, enabling the generalization of findings to the entire production. The choice of an appropriate sampling method depends on the purpose of observation. In some cases, less stringent methods, such as random selection, may be acceptable. The most common approach, however, is the use of random samples.

Two principal groups of sampling designs are distinguished: probability sampling and non-probability sampling [11]:

- Probability sampling involves some form of random selection in choosing the product to be included in the sample. In this method, each product has the same likelihood of being selected.
- Non-probability sampling relies on non-random methods of selection. This type of sampling is considered the least reliable.

The choice between quantitative and qualitative research approaches should be determined by the phenomenon under observation. The objective of the quantitative approach is to test established hypotheses and to produce generalizable results. By contrast, the qualitative approach aims to provide clarification and deeper understanding of the problem. The principal distinctions between quantitative and qualitative research approaches summarizes Tab. 1 [9].

Tab. 1 Comparison of Quantitative and Qualitative Research Approaches [4]

	Quantitative Approach	**Qualitative Approach**
Philosophical Basis	Deductive	Inductive
Objective	To test predefined hypotheses	To explore complex problems
Study Design	Sequential, predetermined	Flexible
Role of the Researcher	The aim is to be objective	The inseparable part of the research process
Quality Assessment of Results	Direct results of validity and reliability ensured through statistics	Methods of indirect quality assurance and credibility
Usefulness of Results	Generalizability	Transferability

The selection of random samples provides generalized results derived from testing. Samples used for qualitative investigations are usually small components. The larger the sample size, the lower the probability of random sampling error. The optimal sample size depends on the parameters of the phenomenon under investigation.
As illustrated in Fig. 3, the objective of sampling is to obtain a sample that best represents the characteristics of the products.

Sampling and the calculation of sample size are fundamental topics in industrial engineering. The reasons are linked to the observations obtained from collected samples and their measurements, since compiling process data and inspecting and testing all products would be both costly and time-consuming.

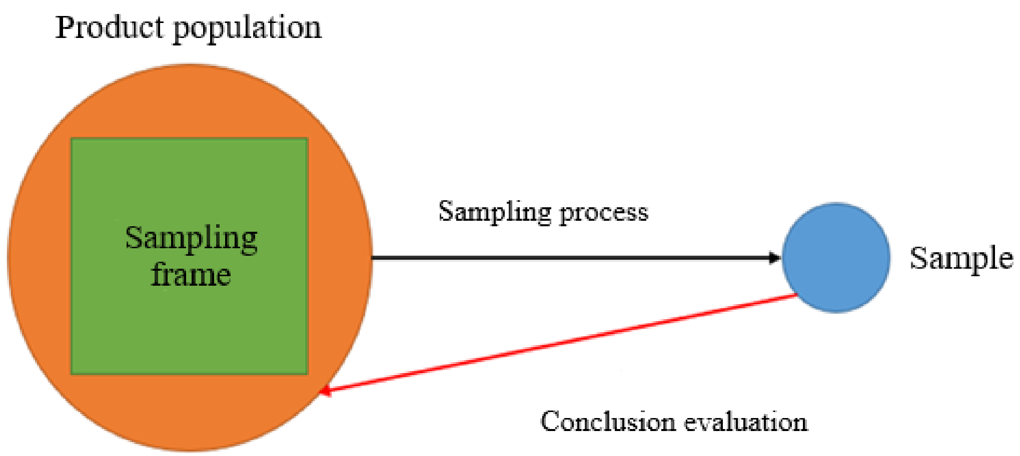

Fig. 3 Objective of Sampling

The intermediary element between the entire production population and the sample selected for research is referred to as the sampling frame. The first step consists of defining and describing the target population, i.e., the group of products of interest. The term population denotes the set of all products. Fig. 4 provides information about the steps in the sampling procedure.

The second step is to determine the sampling frame. The sampling frame refers to the list of products from which the sample is to be drawn. The population size (N) represents the total number of products under consideration.

The next step is to establish the sampling criteria. During this step, the sampling frame is verified, the calibration of the sampling instrument is checked, and, where applicable, the population itself is reviewed. Within this phase of the sampling process, the principle of uncertainty is applied, meaning that the sample should be taken under the same conditions as those present during product manufacturing [4, 10].

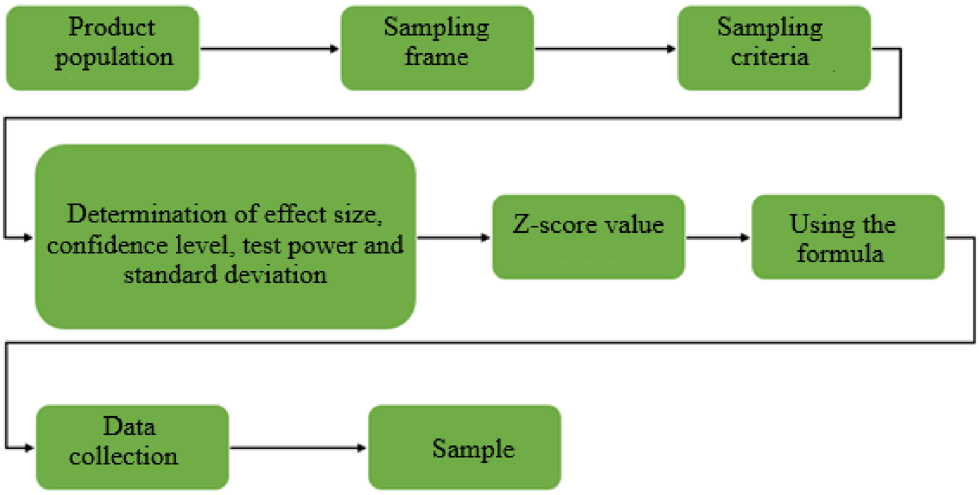

Fig. 4 Sampling steps

It is necessary to define the margin of error (effect size, e). The margin of error or confidence interval indicates the extent of error that is acceptable in the result.

The fifth step is to define the confidence level ($1 - \alpha$). The confidence level represents the degree of certainty that the entire population of products will be accurately represented by the results obtained from the tested sample.

The determination of test power ($1 - \beta$) supports the adjustment of the sample size. This parameter is required to ensure that the data collection process achieves sufficient statistical power.

Another important parameter in sampling is the standard deviation (σ), which expresses the expected degree of variation among the results. If the standard deviation is unknown, a proportional value of $p = 0.5$ (50%) is applied.

It is also essential to set the value of the Z-score. The Z-score is determined based on the selected confidence level.

The calculation of sample size for a small population is given as follows:

$$n = N\left[\frac{\frac{\left(Z_{\alpha/2}+Z_{1-\beta}\right)^2\sigma^2}{e^2}}{N-1+\frac{\left(Z_{\alpha/2}+Z_{1-\beta}\right)^2\sigma^2}{e^2}}\right] \tag{1}$$

The formula for calculating the sample size for a large population is:

$$n = \frac{\left(Z_{\alpha/2}+Z_{1-\beta}\right)^2\sigma^2}{e^2} \tag{2}$$

The sample size based on the proportion from a small population of size *N* is calculated as:

$$n = N\left[\frac{\frac{\left(Z_{\alpha/2}+Z_{1-\beta}\right)^2 p(1-p)}{e^2}}{N-1+\frac{\left(Z_{\alpha/2}+Z_{1-\beta}\right)^2 p(1-p)}{e^2}}\right] \tag{3}$$

The sample size based on the proportion from a large population is determined as:

$$n = \frac{(Z_{\alpha/2}+Z_{1-\beta})^2 p(1-p)}{e^2} \tag{4}$$

Once the sample size has been determined, data collection is required to identify the data points to be included in the sample. At this stage, the sample is considered complete.

With the development of intelligent manufacturing and Industry 4.0, industry continues to advance with an increasing focus on product quality. Enhancing existing digital tools can significantly improve product quality. An intelligent metrological sampling system must be capable of handling current metrological sampling either through time-based or percentage-based rules, and it must be configurable to perform event-driven sampling.
Sampling can be dynamically adapted to production conditions, either those defined within the system itself or those recommended by other common systems, such as Advanced Process Control (APC), Fault Detection and Classification (FDC), and Statistical Process Control (SPC). Visualization and monitoring of metrological sampling are becoming essential to meet the requirements of suppliers in the automotive industry.
An independent metrology management system may either provide insufficient coverage or cause serious disruptions in production scheduling or delivery planning, potentially leading to productivity losses.
Cyber–Physical Systems (CPS) represent a new generation of engineered systems that integrate computational and physical components and form the foundation of the Industry 4.0 concept.
The achievement of optimal design and manufacturing parameters can be ensured through the application of Taguchi principles and theories. The primary objective is to determine optimal levels of multiple design factors within the manufacturing process, thereby achieving minimal costs while maintaining a defined level of quality [2].
While CPS operate online, various parameters change under different operating conditions, which may lead to process performance degradation. Machine wear or damage results in deviations of product characteristics from target values. This, in turn, increases the rate of nonconformities and consequently raises rework costs [5].
Recalibration of machines to their initial design configuration is both time-consuming and costly. Within CPS, however, production parameters can be adjusted more easily. This flexibility allows for cost minimization without the need for complete recalibration of the machines.
The quality of final products in multistage manufacturing processes depends on the specifications applied in preceding stages. These parameters directly influence the proportion of conforming and nonconforming parts in subsequent subprocesses.

Conclusion

The paper demonstrates that the management of nonconforming products is not merely a corrective practice but a fundamental pillar of sustainable manufacturing. By systematically detecting, classifying, and addressing defects, enterprises can reduce waste, improve product reliability, and strengthen customer trust.

The integration of intelligent sampling systems, combined with advanced analytical methods, provides companies with the tools necessary to navigate increasingly dynamic and competitive environments. Technologies such as cyber–physical systems, advanced process control, and statistical process monitoring offer flexible and scalable solutions for reducing defects and ensuring production stability [5].
Ultimately, the successful implementation of Industry 4.0 principles requires a balance between traditional quality management techniques and innovative digital solutions. By leveraging both, enterprises can build resilient manufacturing systems capable of meeting the growing demands for efficiency, customization, and high product quality in global markets.

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OPTIMIZATION OF THE TRANSPORTATION OF OVERSIZED CARGO USING MODERN TECHNOLOGIES

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Abstract: The article presents the issue of improving oversized cargo transport processes through optimization of route planning. Using the example of a small enterprise, a proprietary computer program/application was developed to reduce the time required to determine the optimal route for oversized cargo. The application implements Dijkstra's algorithm in the Python programming language.
Keywords: oversized transport, optimization algorithms, route planning.

Introduction

The contemporary development of a country's economy determines the increasing demand for the transportation of cargo with non-standard dimensions, weight, or shape. The transportation of oversized cargo [8, 9] involves numerous legal, technical, and logistical difficulties. Oversized transport requires not only specialized equipment but, above all, specialized knowledge, qualifications, and employee experience. One of the most important factors influencing the success of a transportation task is the route planning process, and the availability of complete data and its proper use is a determinant of the optimal choice. During the planning process, it is necessary to consider legal regulations that precisely govern aspects related to oversized transport [1, 6, 7, 10]. With the support of modern technologies such as GPS or Galileo navigation systems, we can precisely determine the actual position of the transported cargo. This has a significant impact on safety, time, and costs generated during transport. Advanced TMS programs reduce the time spent on route planning, allowing the selection of the fastest or shortest possible route depending on the preferred factor [3, 11]. This is possible thanks to the use of algorithmic graph search methods such as Dijkstra's algorithm [4].

Methods and methodology.

The issue of route planning optimization was presented using the example of transporting a grain silo with a straight-line distance between target points of 132 km. The company, based on its experience in the industry, developed its own transport planning system using basic tools such as Google Maps, Automapa, and the GDDKiA Map Service. During the planning of oversized cargo transport, a key limitation was identified, namely the lack of adaptation of transport infrastructure to the technical requirements for non-standard transport. Special attention was paid to vertical clearance restrictions under engineering structures such as bridges, viaducts, flyovers, or overhead lines. The occurrence of height restrictions on main communication routes – types A, S, GP, G [6] – leads to a significant extension of the transport planning process.

In the study, Dijkstra's graph algorithm was used, which in transport serves to find the shortest, optimal route in a graph with non-negative edge weights (e.g., distances or costs), transforming points and connections into a network of vertices and edges. The road network is represented by vertices (intersections) and edges (road segments), and the edge weights can reflect distance, travel time, or fuel costs. The algorithm begins at a selected starting point and gradually expands the set of vertices for which the optimal route has been found until the destination is reached [5]. The task of the algorithm is to find every possible route from the starting point to any vertex, calculating the cost associated with the analyzed path. By transforming the algorithm, we can obtain different forms of graph analysis related to the order in which specific edges are examined [2].

Implementacja algorytmu w aplikacji

To optimize planning tasks, an application was developed with the following assumptions:

– The vehicle is treated as an inseparable whole reflecting real parameters.
– There is one sender and one recipient as loading and unloading points.
– The vehicle's parameters remain unchanged throughout the entire route.
– Road infrastructure has properties influencing the final result.

Due to the nature of the work, it was assumed that the best solution for the chosen method would be to use a file-based database, which: for infrastructure dimensions, was prepared based on information provided by the General Directorate for National Roads and Motorways; for edge lengths and travel times, data was obtained from Google Maps and Automapa; for costs, the source of data was the e-Toll website.

The developed CSV file contains data concerning connections between graph nodes, such as distances, travel time, tolls, restrictions, and other data about road segments. The file contains 61 rows and 7 columns. Each column represents an attribute describing the properties of the connection between two nodes:

- Start and end nodes and road number are text data (string).
- Distance, travel time, toll, and height restriction are numeric data (float).
- All columns contain complete data — no empty or missing values.
- Numeric columns are homogeneous in terms of data type.

Data entry into the created application began with the development of an input data catalog for the Python programming language, which was then used as the application database for graph calculations based on Dijkstra's algorithm.

Tab. 13 Summary of vertices and edge weights in the test graph (selected data)

No.	Start node (W1)	End node (W2)	Distance (km)	Travel time (min)	Toll charge (zł)	Route number	Height restriction (cm)
1.	Wrocław	Oława	27	32	0.0	DK94	523
2.	Wrocław	Oleśnica	35	40	0.0	DW368	462
3.	Oleśnica	Kępno	46	34	13.0	E67	482
4.	Kępno	Milicz	67	69	5.28	DK25	350
5.	Milicz	Trzebnica	32	28	0.0	DK15	614
6.	Trzebnica	Wrocław	27	31	6.27	S5	495
7.	Wrocław	Oborniki Śląskie	25	37	0.0	DW342	482
8.	Oborniki Śląskie	Trzebnica	12	16	0.0	DW340	486
9.	Trzebnica	Żmigród	22	20	8.35	S5	482
10.	Załęcze	Żmigród	20	14	5.66	S5	540
11.	Załęcze	Ścinawa	38	36	0.0	DK36	1000
…	…	…	…	…	…	…	…
60.	Zgorzelec	Lubań(objazd)	37	38	0.0	DK30	1000
61.	Lubań	Gryfów Śląski	15	15	0.0	DK30	1000

The algorithm is designed to minimize the traversal cost from the start node W1 (green marker) to the end node W2 (red marker) (Fig. 1).

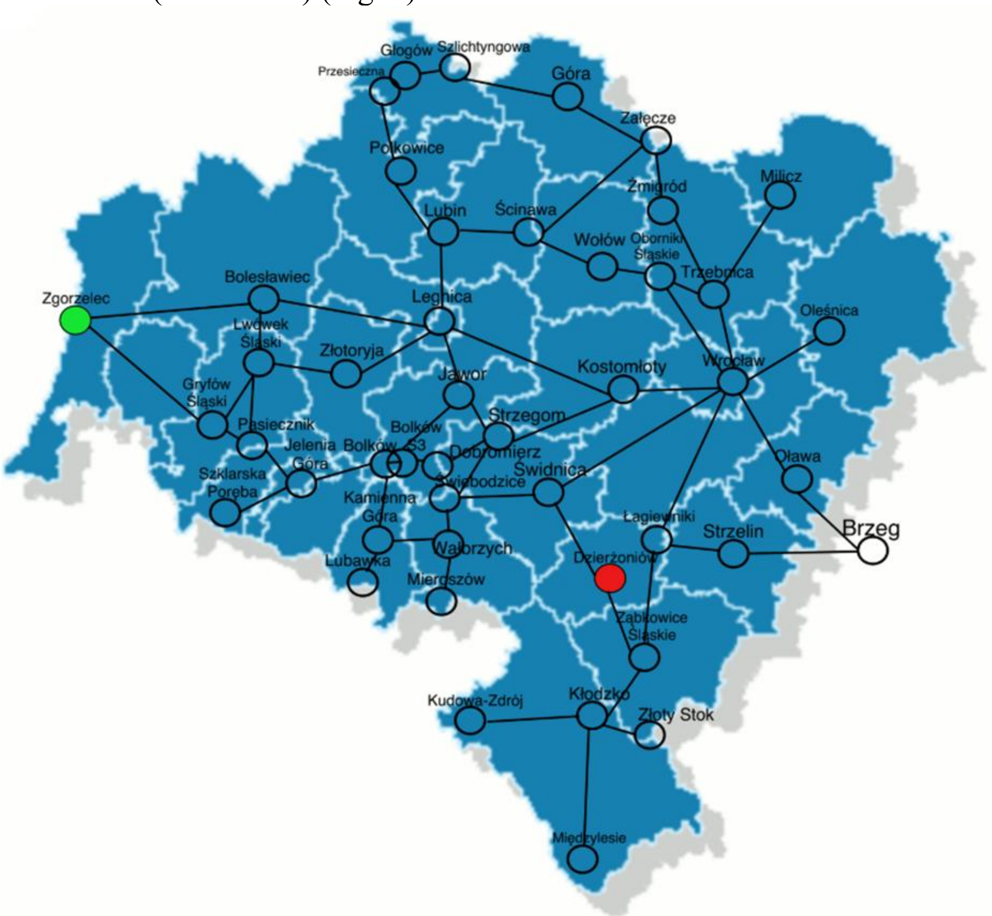

Fig. 1. The graph structure is superimposed on the map of the Lower Silesian Voivodeship

The map depicts the network of roads connecting selected cities within the Lower Silesian Voivodeship. Cities were selected based on road classification (A, S, G, and GP) and their location (major nodes, transport routes, county capitals). Roads of class Z and lower were omitted in the data processing due to the unpredictability of their infrastructure condition, the potential for disruptions, and the risk they may pose to other road users considering lane width. Taking into account operational requirements and the locations of loading and unloading points, the system allows for the addition of custom edges and nodes to the database of the analyzed graph, including their length, travel time, cost, and constraints, either directly within the software or by adding a row in a CSV file.

Application of the route determination method within the software.

The method for determining the feasibility of a non-standard vehicle traversing between two points in the road network is a multi-level procedure. Initially, it requires the specification of input data, which triggers the verification procedures.

The developed method can be divided into the following phases:

1. Graph Initialization – Creation of the graph, including the addition of nodes and edges with specified properties (road length, travel time, cost, road number, height restrictions).
2. Input Data Loading – Enables loading of data from a CSV file containing information about nodes and edges.

3. Vehicle Parameters and Optimization Criteria Definition – Input of vehicle height and assignment of weights to route parameters.
4. Optimal Route Determination – The Dijkstra algorithm calculates the shortest path between nodes, taking height restrictions into account.
5. Path Reconstruction and Analysis – Reconstructs the route and computes its details (total travel time, total length, total cost).
6. The final route selection is based on the minimum cost, considering the weighted prioritization of parameters according to the formula:

$$k = \sum_{n=1}^{N}(length_n \times W_1) + (time_n \times W_2) + (charge_n \times W_3)$$

where:
N – total number of edges in the selected route
W1 – weight for route length
W2 – weight for travel time
W3 – weight for toll costs.

1. Result Output – The application provides a textual response (optimal route with road numbers, costs, length, and travel time). If no feasible route is found based on the input data, feedback is provided regarding the constraints and the roads where they occur.
2. User Interaction – Allows the user to reselect or modify the task.

Results and Discussion.
The study was conducted in two groups: the first continued to operate without the use of the application, as previously, while the second employed the proprietary application (Table 2).

Tab. 2 Series-parallel cycle of the 'Optimal Route Selection' subprocess with support from the mobile application.

Operation	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Familiarization with cargo dimensions	P-1 P-2 P-3					
Determination of loading and unloading points	P-1					
Map analysis and assessment of road availability	P-2; P-3					
Route inventory	P-2; P-3					
Analysis of available route data	P-1; P-2 P-3					
Acquisition of missing data	P-1; P-2	P-2; P-1 P-3				
Risk analysis associated with cargo movement		P-1				
Identification of service points along the route		P-1				
Analysis of current road conditions		P-2	P-2			
Definition of optimization criteria			P-1; P-2 P-3			
Delivery time analysis			P-1			
Travel cost analysis			P-1			
Determination of cargo insurance requirements			P-3			

Preparation of the optimization model			P-1			
Application of height constraints in the mathematical model			P-1;P-2			
Execution of calculations based on input data			P-1; P-2 P-3			
Evaluation of calculation results				P-1; P-2 P-3		
Route visualization				P-1; P-2 P-3		
Selection of the final route				P-1; P-2 P-3; K		
Selection of alternative routes				P-1; P-2 P-3; K		
Preparation of an activity report and database update				P-1; P-2 P-3; K	P-1; P-2 P-3K	

The results of the study conducted before and after the implementation of the route optimization application in the planning process for oversized cargo transport indicate a reduction of 14 hours in the time required for route development (Fig. 2).

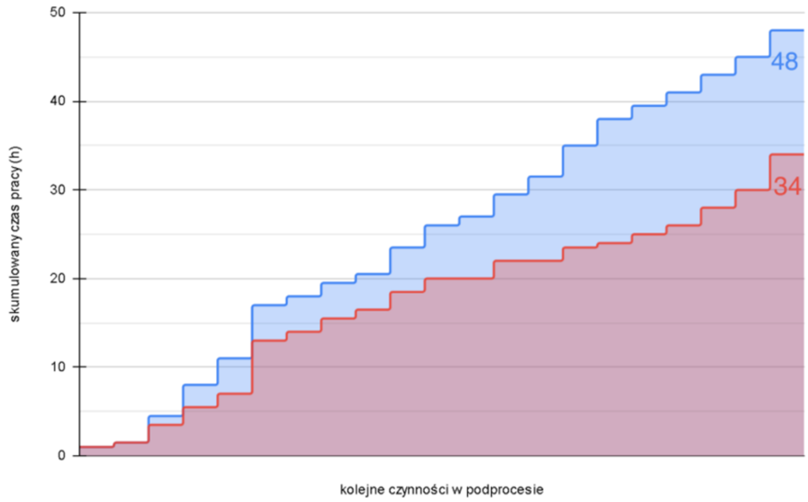

Fig. 2. Cumulative duration of the 'Optimal Route Selection' subprocess: Blue – without the application; Red – with the application.

Conclusions

The implementation of the proposed optimization method resulted in significant benefits for the company by reducing the time required to perform tasks. The conducted study revealed a time reduction of 29% in the 'Optimal Route Selection' subprocess and 9.3% in the overall planning activities. Support of the process through the developed application, combined with a structured database, therefore positively impacts the execution time of individual tasks within the optimal route selection process.

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THE USE OF STATISTICAL METHODS IN THE ASSESSMENT OF ERGONOMIC CONDITIONS IN THE WORKPLACE

Gabriela IŽARÍKOVÁ – Anton HOVANA – Jana KRONOVÁ

Abstract: Ergonomics is a multifaceted science that deals with the improvement of working conditions, in terms of the designed conditions that support effective and comfortable human work. Ignoring ergonomic principles can have negative consequences, such as injuries, fatigue, reduced productivity and errors. Ergonomics and lighting are interrelated aspects of the work environment that affect the health and comfort of the employee. Proper lighting contributes to good visual ergonomics by ensuring sufficient natural and artificial light. Statistical methods allow objective and accurate evaluation of whether the lighting meets the required standards and is evenly distributed. In our contribution, we have examined two classrooms and determined whether the lighting fulfills standards for workplace. However, there are some drawbacks influenced by points of measuring.

Keywords: ergonomics of the environment, illumination intensity, light uniformity, basic statistical indicators

Introduction

Ergonomics plays a crucial role in modern manufacturing, as it enhances working conditions and increases overall process efficiency. Within the workplace, it directly affects product quality. When employees operate in a comfortable environment, they are more focused, make fewer errors, and generate fewer defective products. As an integral part of management systems, ergonomics directly influences work quality, employee well-being, and organizational performance. It encompasses a set of measures aimed at creating optimal working conditions that improve comfort, reduce both physical and mental workload, and mitigate occupational risks. Lighting is an essential part of environmental ergonomics, as it directly affects comfort, performance, and human health during both work and rest. Inadequate or glaring light forces individuals to strain their eyes, squint, or adopt unnatural head positions, which can result in eye strain, as well as neck and back pain. Proper lighting supports alertness, concentration, and reduces fatigue. For detailed manual or computer-based tasks, uniform and sufficient lighting is necessary to prevent errors and avoid micro-movements of the body caused by efforts to see more clearly. Poor lighting can lead to visual fatigue, musculoskeletal pain, and decreased performance. Conversely, well-designed lighting promotes natural posture, a healthy circadian rhythm, and work efficiency. In proper ergonomic design, lighting is just as important as the chair or the height of the desk. Ergonomics is the science of work. The Occupational Safety and Health Administration (OSHA) identifies major ergonomic risks in the workplace and sets requirements for their elimination.

Illumination intensity

The intensity of illumination plays an important role in ensuring visual comfort, work efficiency, and safety. Assessing intensity of illumination is a key factor in providing optimal lighting conditions in both indoor and outdoor spaces. The aim of this article is to demonstrate how statistical methods can be used to analyze and evaluate lighting conditions in different environments. Natural daylight is irreplaceable for humans. Therefore, it should be used purposefully and efficiently. Even at the design stage of interior spaces intended for long-term occupancy, conditions should be created to maximize the use of daylight in line with the function of the given rooms. Ergonomic lighting plays a crucial role in creating safe and comfortable spaces for both work and leisure. This concept includes not only the amount of light in a room but also its quality, uniform distribution, accurate color temperature, glare-free illumination, and the ability to adapt lighting to individual needs. Light has a direct impact on both physical and mental health. In Slovakia, the standard STN EN 12464-1: Light and lighting – Lighting of indoor work places serves as the basis for lighting design.

- **For classrooms, the prescribed minimum illumination level is 300–500 lux** (depending on the type of classroom and the activity).
- **Lighting uniformity should be at least 0.7** (to avoid excessive unevenness of light). In classrooms and offices, the minimum required uniformity is 0.6. For general lighting, it is recommended not to be lower than 0.4.equipment (monitors and projector), which also affects the light distribution. Measurements were made on a working plane at a h (b) and 15:00 (c), at the marked points in the room, Fig. 1. The light measurement device was used to measure the luxmeter DIGITAL LUXMETER, version WT81B.

Measurement conditions

Two classrooms were selected as reference spaces for lighting measurements – a standard classroom (1) and a specialized computer classroom (lab) (2). The size of the first classroom was 7 x 6 meters and the size of the second was 8 x 6 meters. The main source of light was artificial room lighting and natural lighting coming through the windows, additional lighting came from switched-on computer equipment (monitors and projector), which also affects the light distribution. Measurements were made on a working plane at a height of 1 meter above the floor at 8:00 (a), 12:00 (b) and 15:00 (c), at the marked points in the room, Fig. 1. The light measurement device was used to measure the luxmeter DIGITAL LUXMETER, version WT81B.

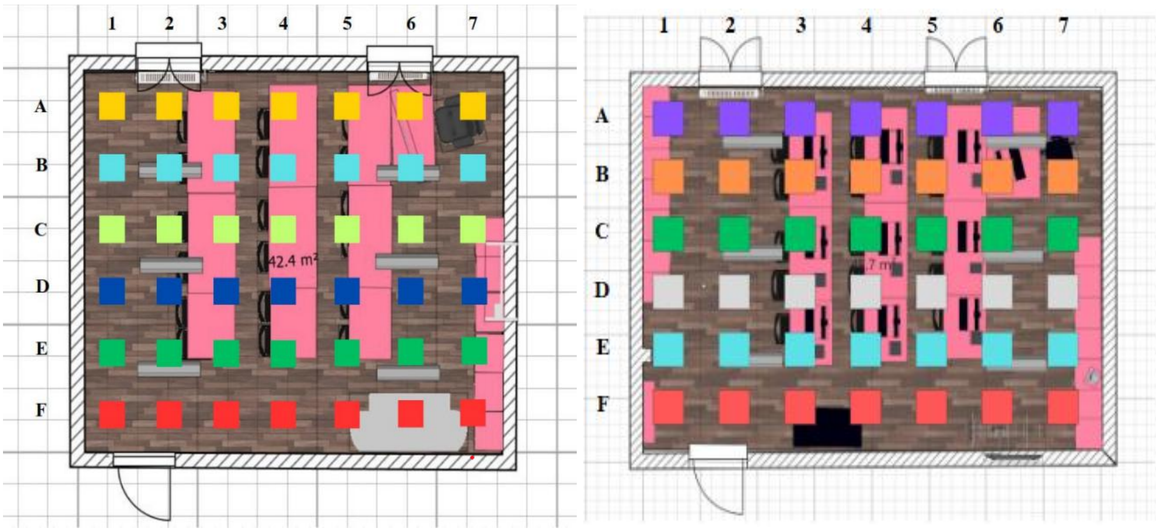

Fig. 1 Floor plan of the standard class and computer lab

Measurement evaluation

[1]Basic statistical indicators used in the assessment of lighting include:

- minimum and maximum values,
- average intensity of illumination,

- standard deviation, coefficient of variability.

These indicators provide a picture of the overall level and variability of lighting in space (Table 1).

Tab. 14 Basic statistical indicators intensity of illumination

	Standard class (1)			*Computer lab (2)*		
Time	**(a)**	**(b)**	**(c)**	**(a)**	**(b)**	**(c)**
Min [LX]	276	299	278	247	283	234
Max [LX]	988	945	771	937	918	845
Average [LX]	551	528	483	534	469	479
Stand. Dev. [LX]	181	175	140	205	169	171
	32.8%	33.2%	29%	38.5%	36%	35.6%
Light uniformity	0.50	0.57	0.58	0.46	0.60	0.49

The recommended average illuminance for standard offices or classrooms is approximately 500 LX, which was achieved in the standard classroom during two measurement instances (a, b). In the case of the computer laboratory, the recommended average illuminance is around 300 LX, and this requirement was consistently fulfilled across all measurements. For offices and classrooms, the recommended coefficient of variation (CV) of illuminance should not exceed 0.3 (30%) to ensure sufficient uniformity of lighting. Values above this threshold indicate uneven light distribution, which may negatively affect both comfort and concentration. In the evaluated rooms, the CV values slightly exceeded the recommended limit, suggesting that the lighting distribution was somewhat irregular. According to general lighting guidelines, illuminance uniformity should not fall below 0.4. However, for classrooms and computer laboratories, standards specify a minimum uniformity of 0.6. This criterion was not met, indicating the presence of pronounced variations in brightness across the space. Such conditions can result in the formation of significantly brighter and darker zones, which may contribute to increased visual fatigue and reduced visual comfort among students.
Subsequently, we examined the differences between the intensity of illumination depending on the time of measurement in the same room. The first we used the Shapiro-Wilk tables to calculate the p-value on the normal distribution. Since p-value > α (α=0.05), we accept the null hypohsis, it is assumed that the data is normally distributed, tab.2.

Tab.2 Result of Shapiro-Wilk test

	Standard class (1)			*Computer lab (2)*		
Time	**(a)**	**(b)**	**(c)**	**(a)**	**(b)**	**(c)**
p-value	0.0936	0.0020	0.0155	0.0010	0.0002	0.0039

Based on the results of the Shapiro-Wilk test, we used non-parametric tests for other evaluation. To compare the values intensity of illumination at different measurement times, we used the Kruskal Wallis test. The *p-value* is 0.2424 (H=2.8342) for the standard class and *p-value* is 0.2374 (H=2.8759) for the computer lab. The result is not significant at $p < 0.05$. We do not reject the null hypothesis. This means that we do not have enough evidence to claim that the time of measurement has an effect on the intensity of illumination.

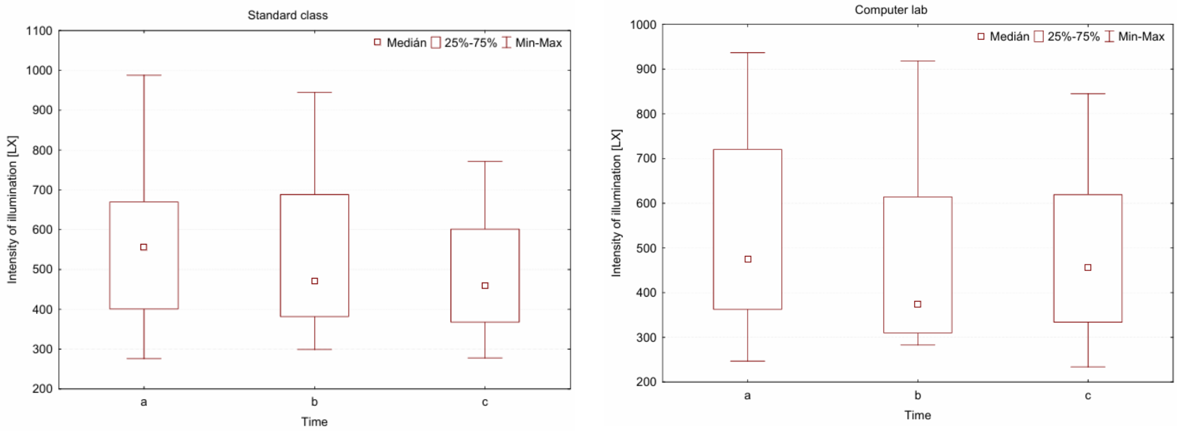

Fig. 2 Comparison intensity of illumination according to measurement time

We used the Mann-Whitney U test to determine the difference between rooms. The *z-score* is 0.63517 (a), *p-value* is 0.5222 (a), the result is not significant at $p < 0.05$ for the time measurement 8:00. The *z-score* is 2.0352 (b), *p-value* is 0.0414 (b), the result is significant at $p < 0.05$ for the time measurement 12:00. The *z-score* is 0.4578 (c), the *p-value* is 0.6527 (c), the result is not significant at $p < 0.05$ for the time 15:00.

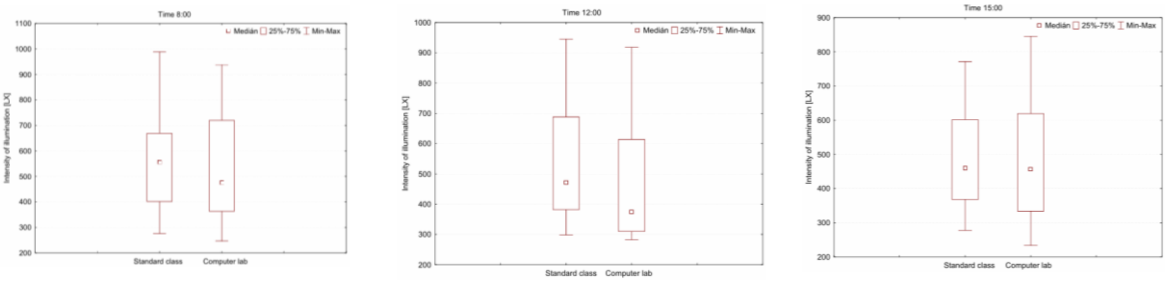

Fig. 3 Comparison intensity of illumination according to class

From Figure 2 and 3, it is evident that the illuminance levels in the standard classroom were consistently higher at all measurement times compared to the computer laboratory. In both rooms, the maximum values were observed at 8:00, followed by a gradual decrease over time. These findings suggest that natural daylight significantly influenced the overall illuminance, particularly during the early morning hours. The subsequent decline may be attributed to changes in daylight intensity of illumination as well as the orientation and structural characteristics of the rooms.

Conclusion

The analysis confirmed that the lighting conditions in the evaluated classrooms only partially met the requirements defined by the standard STN EN 12464-1: Light and lighting – Lighting of indoor workplaces. While the average illuminance values in both rooms were within the recommended range (500 LX for a standard classroom and 300 LX for a computer laboratory), the criteria for illuminance uniformity were not satisfied. The coefficient of variation exceeded the recommended threshold of 0.3, indicating uneven light distribution and the presence of both brighter and darker zones. Such unevenness may negatively affect visual comfort, concentration, and overall learning efficiency. Statistical testing showed no significant differences in illuminance with respect to the time of measurement within the same room.

However, a significant difference between the two classrooms was identified at 12:00, when the illuminance in the standard classroom was substantially higher than in the computer laboratory. This can be attributed to differences in room orientation, daylight availability, and the contribution of additional light sources. Overall, the results highlight the importance of proper lighting design in educational spaces. Adequate and uniform illumination is essential not only for visual comfort and safety but also for supporting effective learning and reducing eye strain. Future improvements in classroom lighting should therefore focus on achieving greater uniformity and optimizing the balance between natural and artificial light.

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EVALUATION AND SELECTION OF SUPPLIERS FOR A COMPANY USING MULTI-CRITERIA DECISION-MAKING – A CASE STUDY

Peter KAČMÁRY – Jakub KOVALČÍK – Kristína KLEINOVÁ – Martin STRAKA

Abstract: This study focuses on the design of a supplier evaluation system for a specific company engaged in the sale and installation of water supply, heating, and sewage materials. The evaluation is based on the application of multi-criteria decision-making (MCDM) techniques, which include key factors such as discount levels, delivery times, supplier reliability, financial situation, and payment and delivery terms. The methodology includes both theoretical and practical analyses using several MCDM methods, with data processed in MS Excel. The findings point to the need for and implementation of MCDM in the strategic selection of a new supplier and highlight the potential benefits for the company's competitiveness.
Keywords: supplier evaluation, multi-criteria decision-making, SCM, logistics.

Introduction

The global business environment is increasingly characterized by complex supply chains, shorter product life cycles, and heightened customer expectations. In such a context, the ability of a company to maintain competitiveness depends not only on its internal efficiency but also on the performance of its suppliers. Supplier selection has become a strategic process that directly influences cost efficiency, product quality, and delivery reliability.

Traditional supplier selection methods often relied heavily on price as the main decision criterion. However, this approach has proven insufficient, as it ignores other critical factors such as reliability, financial stability, flexibility, and partnership potential. In response, companies are increasingly adopting multi-criteria decision-making (MCDM) methods, which allow simultaneous consideration of multiple, often conflicting, factors.

Among these methods, the Analytic Hierarchy Process (AHP) developed by Saaty (1980) has gained particular prominence. It structures complex problems hierarchically and enables decision-makers to make consistent comparisons between criteria and alternatives. In the context of small and medium-sized enterprises (SMEs), AHP provides a systematic yet practical tool for evaluating and selecting suppliers in a transparent and reproducible manner.

This paper presents a case study of a Slovak SME specializing in plumbing, heating, and sewage materials. The company has experienced steady growth in both supplier base and order volumes, creating the need for a more structured approach to supplier evaluation. The objective of this research is to apply pairwise comparison and Saaty’s AHP method to identify the most critical evaluation criteria and to select the most suitable supplier.

Literature review

The problem of supplier evaluation has been extensively studied over the past decades. One of the earliest systematic analyses was carried out by Dickson (1966), who identified 23 criteria influencing supplier choice, including quality, delivery performance, and financial position [1]. His work laid the foundation for subsequent research that increasingly recognized supplier selection as a multi-criteria decision problem.

Later studies have emphasized the role of structured decision-making techniques in supplier evaluation. Weber et al. (1991) reviewed more than 70 articles on vendor selection and concluded that quality, delivery, and cost remain the most frequently applied criteria [2]. More recent literature has expanded the scope of evaluation to include strategic considerations such as sustainability, innovation, and long-term collaboration (Ho et al., 2010) [3].
The Analytic Hierarchy Process (AHP), introduced by Saaty (1980), has become one of the most popular approaches to solving multi-criteria decision problems [4]. It decomposes complex decisions into hierarchical structures consisting of goals, criteria, sub-criteria, and alternatives. Decision-makers express their judgments through pairwise comparisons, which are then converted into numerical weights representing relative importance. AHP also incorporates a consistency check, which ensures logical coherence of expert opinions - an important feature often lacking in purely subjective assessments.
Applications of AHP in supply chain management are widespread. For example, Bhutta and Huq (2002) applied AHP in evaluating global suppliers [5], while Handfield et al. (2002) highlighted its usefulness in aligning supplier selection with corporate strategy [6]. In SMEs, where decision-making is often constrained by limited resources, AHP has proven especially valuable for providing structured yet adaptable evaluation frameworks.

Given its flexibility and mathematical rigor, AHP is particularly well-suited for the supplier selection challenges faced by the described company, where both financial and non-financial factors must be considered.

Method and methodology

The methodology adopted in this study is based on the principles of multi-criteria decision-making, with a particular focus on pairwise comparison and Saaty’s AHP method. The process was designed to ensure both theoretical soundness and practical applicability within the SME context.
Step 1: Identification of Evaluation Criteria:

Drawing on literature (Dickson, 1966, Weber et al., 1991, Ho et al., 2010) and consultations with company experts, five key criteria were identified for supplier evaluation [1-3]:

1. **Product price** (or possible discounts or the financial advantage provided by the supplier). The size of the discount can be expressed as a percentage of the original price or as a fixed amount.
2. **Delivery time**. The delivery time refers to the time interval between placing an order and the delivery of products by the supplier.
3. **Reliability**. Reliability refers to a supplier's ability to minimize and address errors and deficiencies in their products, services, or processes.
4. **Financial stability**. It is important to analyse various financial indicators that provide information about the financial situation and stability of the potential supplier when deciding on a supplier.
5. **Delivery and payment conditions.** The criterion of payment and delivery terms affects the financial and logistical aspects of the business relationship between a supplier and the company.

These criteria reflect both operational and strategic considerations relevant to the company [7].

Step 2: Pairwise Comparison:

Experts from company and university were asked to compare each criterion against the others using Saaty’s fundamental 1 - 10 scale, where 1-2 denotes very low or low importance, 4 indicates moderate importance of one criterion over another, 6 indicates strong importance, 8 very strong, and 10 extreme importance. Odd values were used for finer distinctions [7].

Step 3: Normalization and Weight Calculation

The comparison matrix was normalized by dividing each element by the sum of its column. Row averages were then computed to derive the normalized weights of criteria. These weights represent the relative importance of each criterion in the supplier evaluation process (see results in Tab. 1)

Tab. 15 The resulting values of weights

Criterion	**Product price**	**Delivery time**	**Reliability**	**Financial stability**	**Delivery and payment conditions**
Weight	8.7	7	7.3	3	5

Step 4: Evaluation of Suppliers

Once the weights of criteria were determined, each supplier was evaluated against them. Scores for suppliers on each criterion were multiplied by the corresponding weights and aggregated to produce a final ranking (see graphical interpretation in Fig. 1).

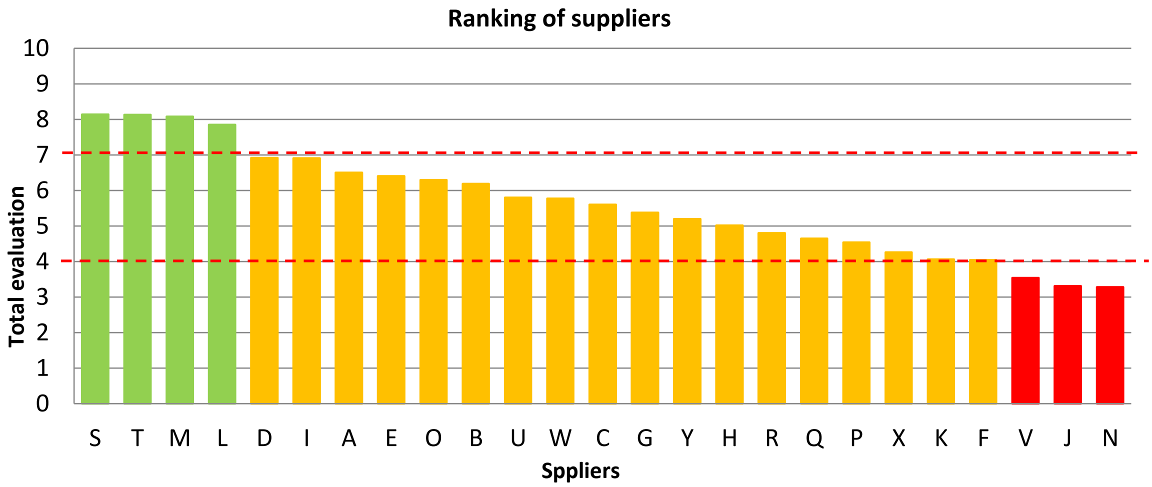

Fig. 1 Ranking of suppliers based on the overall usefulness of individual variants

Source: authors

Results

Now it is clear that the last three suppliers received a rating below the minimum tolerance, i.e. less than 4, based on the evaluation of suppliers (Fig. 1). This prompted the company to change these suppliers soon. They want to start this replacement process with supplier “N,” which was rated the worst of all. Three companies have been identified to replace it, which will be included in the next evaluation of new suppliers as variants (V_1, V_2, and V_3).

In the case of a new supplier evaluation, they reliability cannot be considered as it is not yet known (how often they will deliver faulty goods or late deliveries rate). However, the other criteria may remain the same, as sales representatives seeking to establish new cooperation provide information about the prices and discounts they can offer, their delivery and payment conditions, minimum order quantity or minimum total price of an order to be shipped to a customer and benefits such as discounts for large orders, additional services or technical support, loyalty programs, or financing options [8,9]. Thus, the criteria are:

A. Product price.
B. Delivery and payment conditions.
C. Minimum order quantity.
D. Other advantages.

Tab. 2 Evaluated comparison of criteria

Criterion	A	B	C	D
A	1	9	7	5
B	0.11	1	0.33	5
C	0.14	3	1	1
D	0.20	0.20	1	1
Σ	1.45	13.20	9.33	12

Tab 3. Balancing of the evaluation matrix

Criterion	A	B	C	D
A	0.68	0.68	0.75	0.42
B	0.08	0.08	0.04	0.42
C	0.10	0.23	0.11	0.08
D	0.14	0.02	0.11	0.08

This preparation (calculations in Table 2 and Table 3) is followed by the calculation of normalized weights by geometric average (see Tab. 4).

Tab. 3 Normalised weights calculation

Criterion	A	B	C	D	$\sqrt[4]{\Pi}$	Normalised weights α_i
A	0.68	0.68	0.75	0.42	0.6178	0.68
B	0.08	0.08	0.04	0.42	0.1018	0.11
C	0.10	0.23	0.11	0.08	0,1193	0.13
D	0.14	0.02	0.11	0.08	0,0705	0.08
Σ	4.00				0.9094	1.00

All three suppliers (variants $V_1 – V_3$) have common characteristics: they are leaders in the field of building services engineering, they are a wholesaler, they have an e-shop for installation companies, they have a wide network of stores and, therefore, distribution warehouses.

Tab. 4 Evaluation of variants regarding the criterion

Supplier (variant)	Product price	Delivery & payment conditions	Minimum order quantity	Other advantages
V1	5	3	4	2
V2	4	5	2	1
V3	3	4	5	4

Tab. 5 New potential supplier (variant) evaluation

Supplier (variant)	Product price	Delivery & payment conditions	Minimum order quantity	Other advantages	**Variant evaluation**
V1	1	0	0,067	0,33	**0,71511**
V2	0,5	1	0	0	**0,45**
V3	0	0,5	1	1	**0,265**
Weights	0,68	0,11	0,13	0,08	

The result of MCDM is the most suitable variant 1, i.e., supplier marked with number 1.

Conclusion

The presented study addressed the problem of supplier evaluation and selection in a small and medium-sized enterprise by applying multi-criteria decision-making (MCDM) methods, with particular emphasis on Saaty’s Analytic Hierarchy Process (AHP). Five principal evaluation criteria—product price, delivery time, reliability, financial stability, and delivery and payment conditions—were identified through a combination of literature review and expert consultation. These criteria reflect both operational efficiency and strategic relevance for the company under consideration.

The empirical results confirmed that the systematic application of pairwise comparison and weight calculation provides a transparent and reproducible framework for supplier assessment. This approach facilitated the identification of underperforming suppliers, supported the decision to initiate replacement, and guided the evaluation of potential new partners. Even in cases where certain criteria (e.g., supplier reliability) cannot be fully assessed for new entrants, the MCDM framework allows the decision-making process to remain objective and consistent. The findings underscore the importance of structured decision-making in supply chain management, especially for SMEs, where resources are limited yet supplier performance significantly affects competitiveness. By adopting MCDM methods, companies can balance multiple, and at times conflicting, criteria in a rational way, thereby strengthening their supplier base and improving long-term sustainability. Future research should consider extending the model to incorporate additional dimensions such as environmental sustainability, innovation capacity, and digital integration, which are becoming increasingly relevant in modern supply chains.

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WHEN THE BASIC THING SEEMS HARD

Anton HOVANA – Gabriela IŽARÍKOVÁ

Abstract: Currently, there are ongoing discussions in Slovakia about whether it is appropriate to introduce a mandatory mathematics final exam at secondary schools. As active university teachers, we believe that the approach to teaching mathematics must first be changed before implementing major educational reforms. In this contribution, we provide a general overview of solving quadratic equations supported by suitable examples – something that an incoming university student should be familiar with, although the reality is often different.

Keywords: quadratic function, equation, solution.

Introduction

Since elementary school, every student encounters the concept of an equation during math lessons. This concept is closely related to the concept of a function, whether it is linear, quadratic, logarithmic, or similar. Each mentioned function has corresponding types of equations that students learn to solve using specific methods.

Since each function can be represented by a graph, solving the corresponding equation means finding the coordinates of the point(s) where the graph intersects the x-axis. It is worth mentioning that we are looking only for x-intercept because the y-intercept is obviously zero.

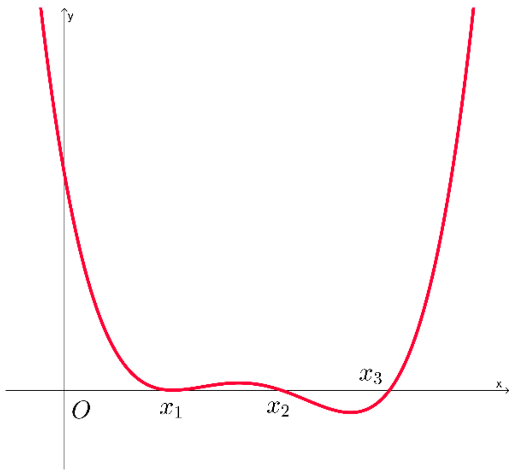

Fig. 1 Intersections of a graph of function (red line) with x-axis

Naturally, there may be multiple such points, see Fig.1, or there may be none, which corresponds to the number of solutions. Given the formula of a function $f(x)$, finding the x-intercepts mathematically means solving the equation $f(x) = 0$. Solution of the equation is sometimes called a root of equation.

In calculations, equivalent or consequential transformations may be used. In the case of applying consequential transformations, it is necessary to verify a correctness of the solution to ensure that it satisfies – or does not satisfy – the original equation. However, if we determine the conditions for the expressions involved before solving, the use of consequential

transformations becomes equivalent transformations, and the correctness check is no longer needed.
In our contribution, we focus on one type of equation – specifically, the quadratic equation. We will demonstrate the classical approach to solving this type of equation, as well as mentioning some interesting alternative solution methods.

Functions lead to equalities
The general quadratic function has an expression
$$f(x) = ax^2 + bx + c,$$
where $a, b, c \in \mathbb{R}$ and $a \neq 0$. The graph is parabola, see Fig. 2.

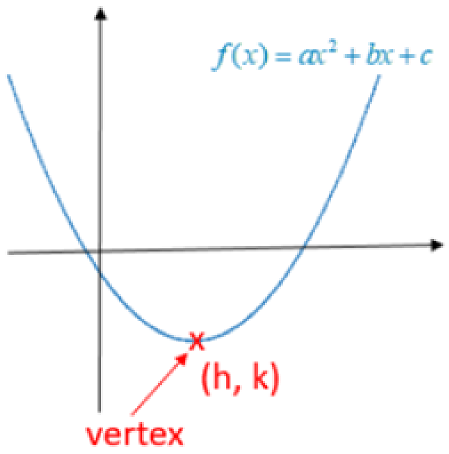

Fig. 2 Parabola – the graph of quadratic function

Thus, the general form of the quadratic equation is
$$ax^2 + bx + c = 0, \qquad (1)$$
where $a, b, c \in \mathbb{R}$ and $a \neq 0$. In case $a = 1$, then the equation
$$x^2 + bx + c = 0, \qquad (2)$$
is called the quadratic equation in its normalized form, see [1]. According to the Fundamental Theorem of Algebra, every algebraic equation of degree n has exactly n (complex) roots. In our case, we are dealing with a second-degree equation. According to the sign of a, it means positive and negative, the graph is convex and concave, respectively, but it does not affect the solution of equation.
Methods of solutions
We show how to solve the equation (1). At first, we consider two special cases.

i) If $b = 0$, then the equation (1) takes the form
$$ax^2 + c = 0 \Leftrightarrow x^2 = -\frac{c}{a} \Leftrightarrow x = \pm\sqrt{-\frac{c}{a}}$$
which has real roots for $\frac{c}{a} \leq 0$. In such a case, the equation can be rewritten in the normalized form $x^2 - \frac{c}{a} = 0$, and by using the algebraic identity $a^2 - b^2 = (a - b)(a + b)$, it can be transformed into factored form $\left(x - \sqrt{\frac{c}{a}}\right)\left(x + \sqrt{\frac{c}{a}}\right) = 0$. If $\frac{c}{a} > 0$, the equation has complex

roots, namely $x = \pm\sqrt{\frac{c}{a}}\,i$. One of the most common mistakes when solving within the set of real numbers is failing to consider the negative root. For example, the equation $4x^2 - 9 = 0$ can be factorized $(2x-3)(2x+3) = 0$, thus the solutions are $x = \pm\frac{3}{2}$, which is sometimes rewritten as $x_1 = \frac{3}{2}$ and $x_1 = -\frac{3}{2}$. When considering the equation $x^2 + 17 = 0$, then $x^2 = -17 \Leftrightarrow x = \pm\sqrt{17}i$.

ii) If $c = 0$, then the equation (1) takes the form

$$ax^2 + bx = 0 \Leftrightarrow x(ax+b) = 0 \Leftrightarrow x = 0 \; and \; ax + b = 0 \Leftrightarrow x_1 = 0 \; and \; x_2 = -\frac{b}{a}.$$

One of the most common mistakes in solving such equations is transforming the equation into the form $ax^2 = -bx$, and dividing both sides by x, which leads to the solution $x = -\frac{b}{a}$. However, since one of the solutions in this case is $x = 0$, and dividing by zero is undefined, this operation is considered incorrect because the initial condition $(x \neq 0)$ was not specified. For example, the equation $5x^2 + 2x = 0$ can be reformulated into $x(5x+2) = 0$ and the roots are $x_1 = 0$ and $x_2 = -\frac{2}{5}$.

A natural question arises whether we can solve this equation in a similar way as in the previous case – that is, by rewriting it so that the left-hand side of the equation becomes a squared expression and the right-hand side of the equation is a number. This transformation is known as completing the square which is described below step by step. The main idea is a suitable application of algebraic identity $(a \pm b)^2 = a^2 \pm 2ab + b^2$, see [5].

$$ax^2 + bx = 0 \Leftrightarrow a\left(x^2 + \frac{b}{a}x\right) = 0$$

$$a\left[\left(x + \frac{b}{2a}\right)^2 - \frac{b^2}{4a^2}\right] = 0 \Leftrightarrow \left(x + \frac{b}{2a}\right)^2 = \frac{b^2}{4a^2}$$

$$x + \frac{b}{2a} = \pm\frac{b}{2a} \Leftrightarrow x_1 = -\frac{b}{2a} + \frac{b}{2a} \; and \; x_2 = -\frac{b}{2a} - \frac{b}{2a} \Leftrightarrow x_1 = 0 \; and \; x_2 = -\frac{b}{a}.$$

If $b, c \neq 0$, then the equation (1) is also called the quadratic equation in complete form. As in the previous case, we demonstrate how to solve the equation (1) by completing the square. We obtain

$$ax^2 + bx + c = 0 \Leftrightarrow a\left(x^2 + \frac{b}{a}x + \frac{c}{a}\right) = 0$$

$$a\left[\left(x + \frac{b}{2a}\right)^2 - \frac{b^2}{4a^2} + \frac{c}{a}\right] = 0 \Leftrightarrow \left(x + \frac{b}{2a}\right)^2 = \frac{b^2}{4a^2} - \frac{c}{a}$$

$$x + \frac{b}{2a} = \pm\sqrt{\frac{b^2}{4a^2} - \frac{c}{a}} \Leftrightarrow x = -\frac{b}{2a} \pm \sqrt{\frac{b^2}{4a^2} - \frac{c}{a}}$$

If we rewrite the expression under the square root with a common denominator, we can simplify it partially by taking the square root. We obtain:

$$x = -\frac{b}{2a} \pm \sqrt{\frac{b^2 - 4ac}{4a^2}} = -\frac{b}{2a} \pm \frac{\sqrt{b^2 - 4ac}}{2a} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \qquad (3)$$

If we denote $D = b^2 - 4ac$, we arrive at the commonly taught method of solving quadratic equations using the discriminant, which is, in a way, a universal approach.

- If $D > 0$, the equation has two distinct real roots.
- If $D < 0$, the equation has a pair of complex conjugate roots.
- If $D = 0$, the equation has one real double root.

The graphical interpretation of the solution in the set of real numbers can be seen in Fig. 3.

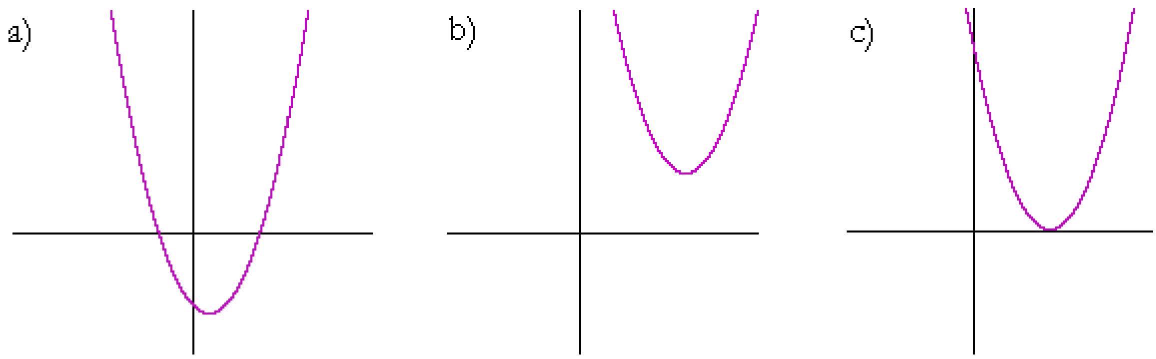

Fig. 3 Graphical visualization of solutions when a) D>0, b) D<0 and c) D=0

Considering the equation $3x^2 + 19x - 14 = 0$. It is easy to see that $a = 3$, $b = 19$ and $c = -14$. Then $D = 19^2 - 4.3.(-14) = 529$ and the roots are $x = \frac{-19\pm\sqrt{529}}{6} = \frac{-19\pm23}{6}$ if and only if $x_1 = \frac{2}{3}$ and $x_2 = -7$.

Let x_1 and x_2 be the roots of the equation (1). Then the expression

$$ax^2 + bx + c = a(x - x_1)(x - x_2)$$

is called the factorization of a quadratic trinomial into root factors. For the normalized form of the quadratic equation (2), we can write:

$$x^2 + bx + c = (x - x_1)(x - x_2) = x^2 - (x_1 + x_2)x + x_1 * x_2,$$

from which another method of solving quadratic equations arises – comparing coefficients, known as Vieta’s formulas: for the roots of the quadratic equation (2), the following must hold: $b = -(x_1 + x_2)$ and $c = x_1 * x_2$. In that case, Vieta’s formulas become especially useful for solving quadratic equations by searching for integer roots. Since the product $x_1 * x_2 = c$ and the sum $x_1 + x_2 = -b$, we can look for integer pairs whose product is c and whose sum is $-b$. This method is particularly effective for simple quadratic equations with small integer coefficients. For example, when solving the equation $x^2 - 6x + 5 = 0$ one can see that $5 = 1 * 5$ or $5 = (-1) * (-5)$, but only the first possibility fits the condition for the coeficient b. Thus, the roots of the considered equation are $x_1 = 1$ and $x_2 = 5$. The most common mistake in this method of solving is the incorrect use of signs.

However, this method becomes difficult to apply in cases where $|a| \neq 1$, because after converting the equation to its normalized form, the coefficients b and c may no longer be integers, making it harder to identify integer root pairs using Vieta's formulas. In this situation, students turn their solution by usage of discriminant. In cases when the coefficient a is a perfect square, it means being $4, 9, 16$, and so on, the coefficient a can be written as $a = A^2$ for some integer A and then the factorization into root factors can be expressed $(Ax - x_1)(Ax - x_2) = 0$ and the Vieta formulas should be modified in the following way: for the roots Ax_1 and Ax_2 must hold $A(x_1 + x_2) = -\frac{b}{A}$ and $A^2 x_1 * x_2 = c$. For example, for the equality $25x^2 - 10x - 3 = 0$ it must hold $5(x_1 + x_2) = -\frac{10}{5} = -2$ and $25x_1 * x_2 = -3$. So, for the coefficient c we have $-3 = 1 * (-3)$ and $-3 = 3 * (-1)$. One can see that the second one is the suitable possibility, and we can write $25x^2 - 10x - 3 = (5x - 3)(5x + 1) = 0$, from which it can derived that $x_1 = \frac{3}{5}$ and $x_2 = -\frac{1}{5}$.

Another way how to successfully apply Vieta´s formulas when the coefficient a is not the perfect square is based on the invariance of the discriminant, meaning its value remains unchanged – and therefore, the number of solutions is the same. For example, it is obvious that the discriminant of the equation (1) and the equation $cx^2 + bx + a = 0$ is the same. Thus, considering the equation (1) which roots are expressed by (3) and its modified version

$$x^2 + bx + a * c = 0. \qquad (4)$$

For the roots of equation (4) it holds

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2} \Leftrightarrow x_1 = \frac{-b + \sqrt{D}}{2} \; and \; x_2 = \frac{-b - \sqrt{D}}{2}.$$

When comparing these to solutions from (3), it follows that the solutions of the original equation (1) can be obtained from the modified version by dividing each solution by the coefficient a, see [2]. Indeed, for the equation $3x^2 + 10x + 7 = 0$ its modified form has the expression $x^2 + 10x + 21 = 0$. Then by Vieta´s formulas we have that $x_1 + x_2 = -10$ and $x_1 * x_2 = 21$ and from the coefficient c we get several options as $21 = 1 * 21$, $21 = (-1) * (-21)$, $21 = 3 * 7$ and $21 = (-3) * (-7)$. It is easy to see that only the last one fulfills the condition for the coefficient b. Then the roots of the original equations are $x_1 = -\frac{3}{3} = -1$ and $x_2 = -\frac{7}{3}$.

By rationalizing the fraction (3) used to compute the roots, we can derive a new expression.

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \cdot \frac{\left(-b \mp \sqrt{b^2 - 4ac}\right)}{\left(-b \mp \sqrt{b^2 - 4ac}\right)} = \frac{b^2 - b^2 + 4ac}{2a\left(-b \mp \sqrt{b^2 - 4ac}\right)} = \frac{2c}{-b \pm \sqrt{b^2 - 4ac}}.$$

A disadvantage of this formula is its application to solving the quadratic equation without a constant term, it is when $c = 0$. In that way one can obtain indefinite expression.

Application

Here, we present several unsolved problems where the quadratic equation appears in the process of solution.

Problem 1: If the area of rectangle is $300\ cm^2$ which breadth is x and length is $2x + 1$, find its dimensions.

Problem 2: In the right triangle it holds that its legs are x cm and $x + 7$ cm long and its hypotenuse is $x + 8$ cm long. Find each length.

Problem 3: A cottage industry produces a certain number of pottery articles in a day. It was observed on a particular day that the cost of production of each article was 3 more than twice the number of articles produced on that day. If the total cost of the production on that day was 90 €, find the number of articles produced an the cost of each article.

Problem 4: The population of the special type of bacteria follows the relation $P(t) = 2^{220+38t-3t^2}$. Find the time when the population will be half of its initial value.

Conclusion

The quadratic equation, as one of the most fundamental algebraic expressions, offers a rich ground for developing problem – solving skills. Through this contribution, we have examined standard solution methods – including factoring, completing the square, and the discriminant approach – as well as alternative strategies based on Vieta's formulas and transformations. For more methods we refer to [3] and [4]. Each method has its own advantages, depending on the form and structure of the equation. We have also emphasized the importance of understanding conditions for real, complex, and double roots, supported by both analytical and graphical interpretations. Finally, we illustrated the practical use of quadratic equations in various real – world scenarios. This broad perspective not only deepens mathematical understanding but also fosters the ability to flexibly choose the most effective solving technique for a given problem.

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THE RELATIONSHIP BETWEEN SELECTED CHARACTERISTICS OF SLOVAK MANUFACTURING COMPANIES AND THEIR PRODUCT ECO-INNOVATIONS

Juraj ŠEBO

Abstract: This paper examines the relationship between selected characteristics of Slovak manufacturing companies and their product eco-innovations. Using data from the European Manufacturing Survey, the study analyzes how firm size, R&D activity, employee involvement, training, environmental management certification, and the use of digital tools such as PLM and design simulation software influence the adoption of product eco-innovations. The results reveal that only 26% of Slovak manufacturing firms implement product eco-innovations, with energy reduction being the most common type. Larger firms, those conducting internal R&D, involving employees in innovation, providing training, and using PLM/PDM systems are significantly more likely to adopt product eco-innovations. Conversely, environmental certification and product design simulation software show limited impact.

Keywords: eco-innovation, product, innovation, Slovakia, manufacturing

Introduction

Eco-innovation, defined as the development and application of new products and processes that contribute to environmental sustainability, is essential for addressing global environmental challenges [1]. However, despite its recognized importance, Slovakia remains among the group of moderate innovators, with an innovation performance below the European Union average [2]. According to [4], one of the main barriers is the insufficient connection between research and development (R&D) and companies that could apply new ideas in practice.

In addition, eco-innovation has been shown to positively influence the environmental, economic, and social development of companies that gradually adopt sustainable practices [2]. However, the traditional approach to evaluating innovation in Slovakia has focused mainly on economic outcomes, often neglecting the ecological dimensions of sustainability and their relevance to consumers [3]. Addressing this imbalance requires a shift toward understanding innovation not only as an economic driver but also as a means of achieving environmental and social progress.

Therefore, this paper aims to evaluate product eco-innovation in Slovak manufacturing companies.

Methodology

This study is based on quantitative data collected in the European Manufacturing Survey. The analysis focuses on Slovak manufacturing companies and examines eco-innovation from multiple perspectives, including firm size, research and development (R&D) activity, target market orientation (B2B vs. B2C), employee involvement, environmental management certification, training practices, and use of digital tools such as PLM and design simulation software.

Results and discussion

Only 26% of Slovak manufacturing firms currently implement product-oriented eco-innovations in their new products (Fig. 1).

Among companies implementing these product eco-innovations, the most common type is energy reduction (12% of all manufacturing companies). Other types are less common (pollution reduction (7%), easier maintenance (7%), improved recycling (6%) and extended product lifespan (5%)).

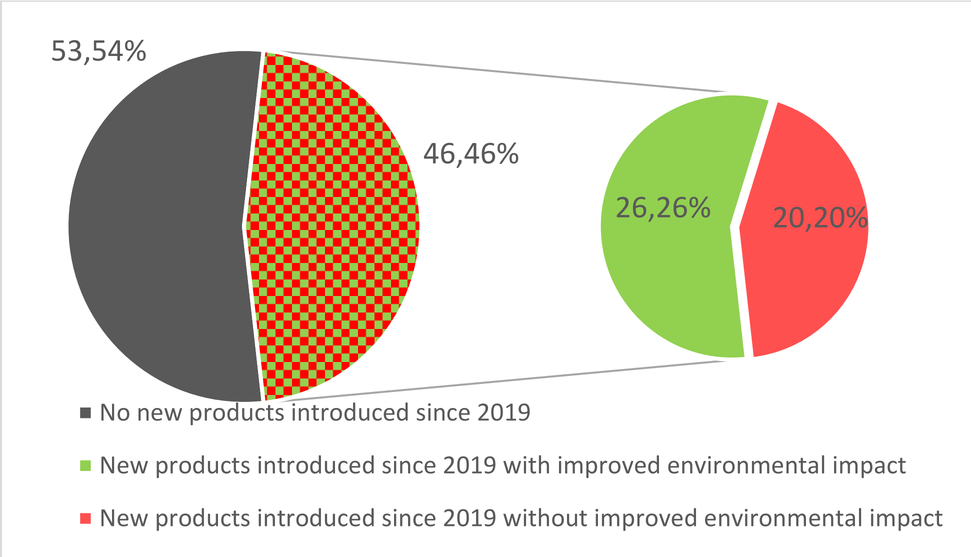

Fig. 1 Product eco-innovation share (calculated from [5])

Only 19% of small firms (<50 employees) introduce new products with improved environmental impact, compared to 29% of medium-sized and 53% of large firms (>250 employees) (Fig. 2).

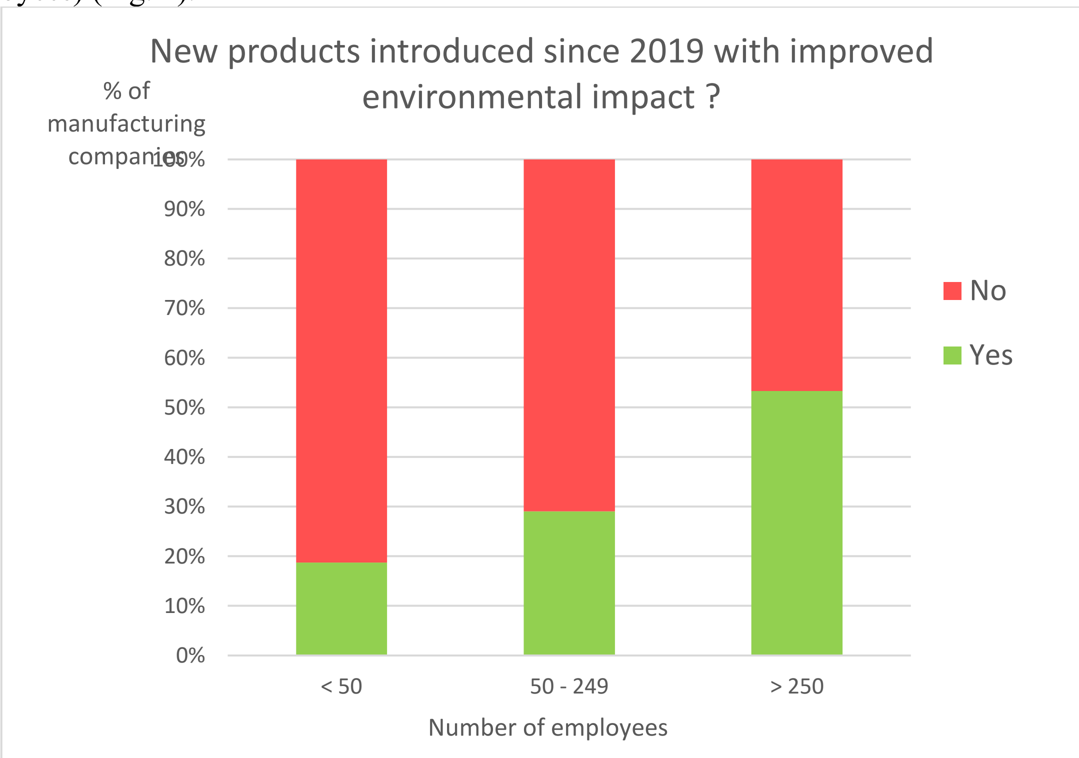

Fig. 2 Firm Size and Product Eco-Innovation (calculated from [5])

Our results show eco-innovation is more prevalent among companies involving employees in innovation (50% eco-innovators) than those that do not (15% eco-innovators) (Fig. 3).

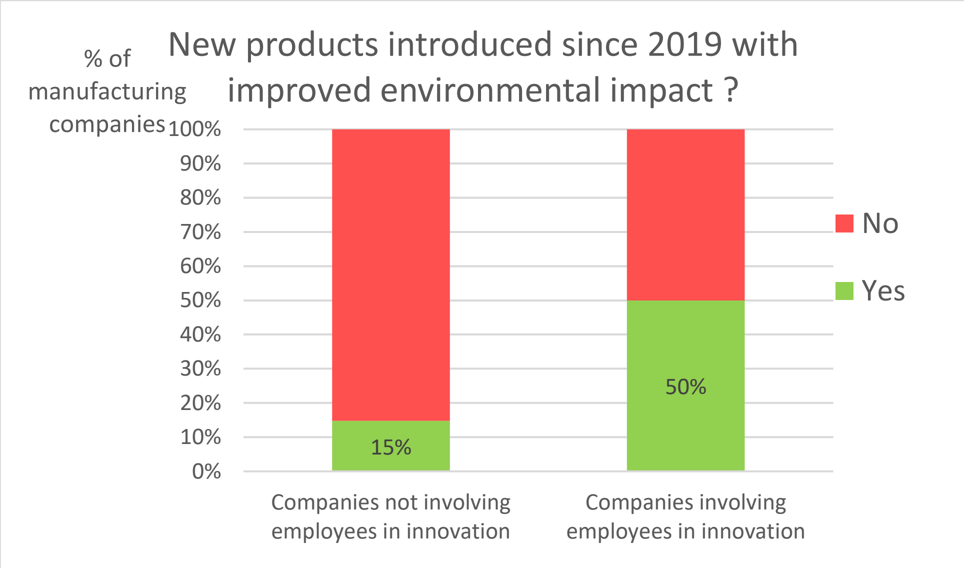

Fig. 3 Employee Involvement and Product Eco-Innovation (calculated from [5])

A clear positive trend is observed among companies offering innovation-related training (52% eco-innovators) versus those that do not (21% eco-innovators) (Fig. 4).

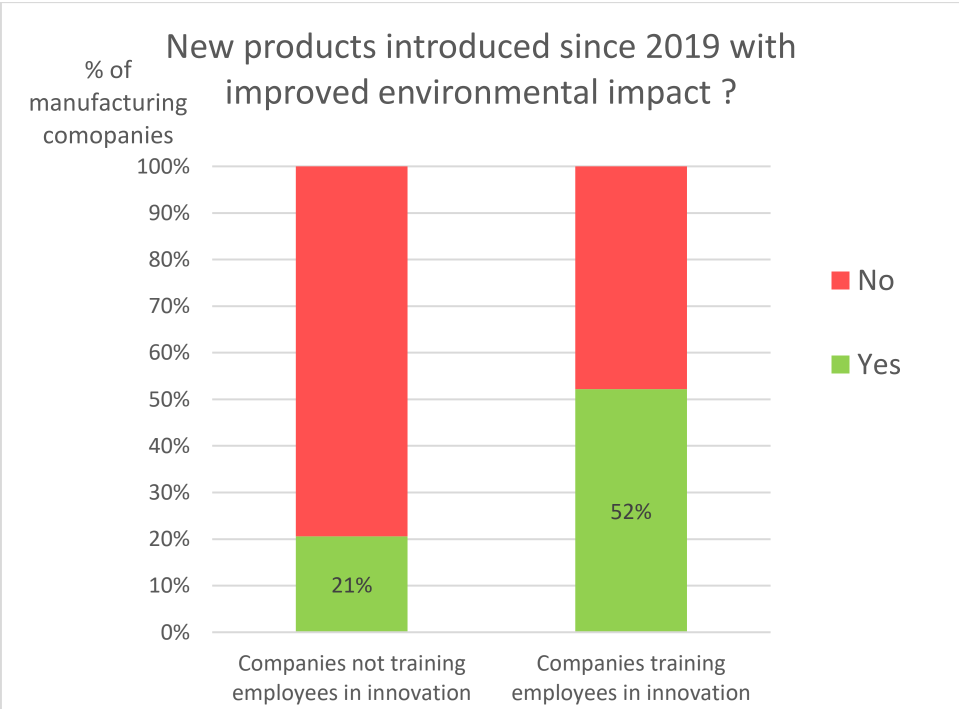

Fig. 4 Training Programs and Product Eco-Innovation (calculated from [5])

Firms conducting internal R&D are significantly more likely (61% eco-innovators) to engage in product eco-innovation than those that do not (20% eco-innovators) (Fig. 5).

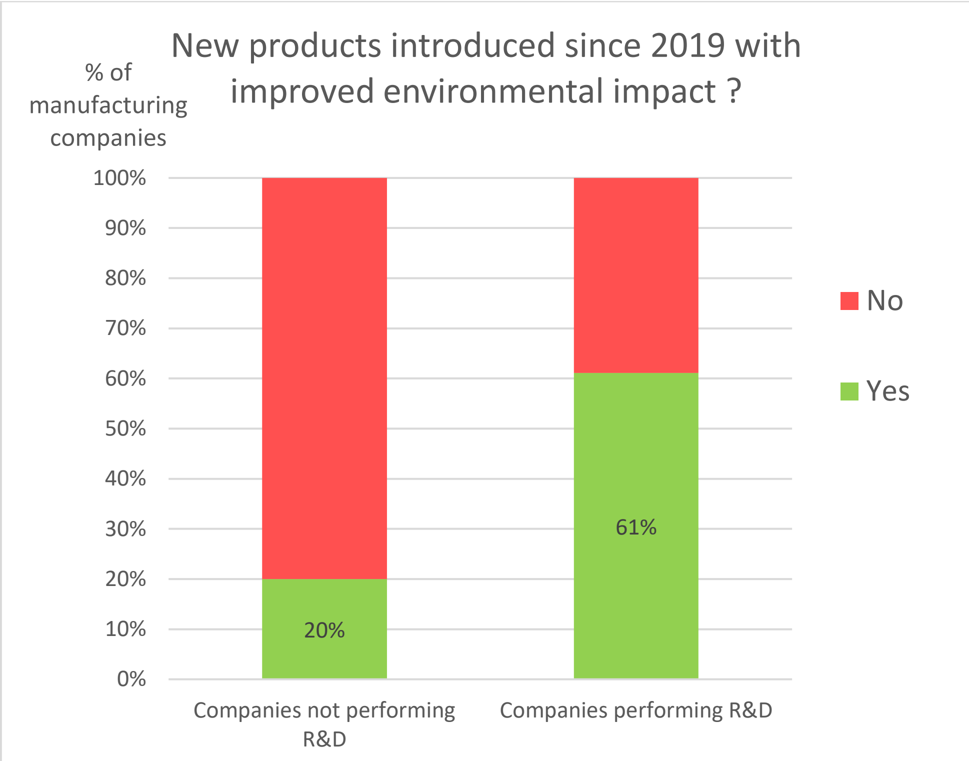

Fig. 5 R&D and Product Eco-Innovation (calculated from [5])

Firms with certified environmental management systems exhibit nearly equal eco-innovation rates (35% eco-innovators) compared to uncertified firms (27% eco-innovators) (Fig. 6).

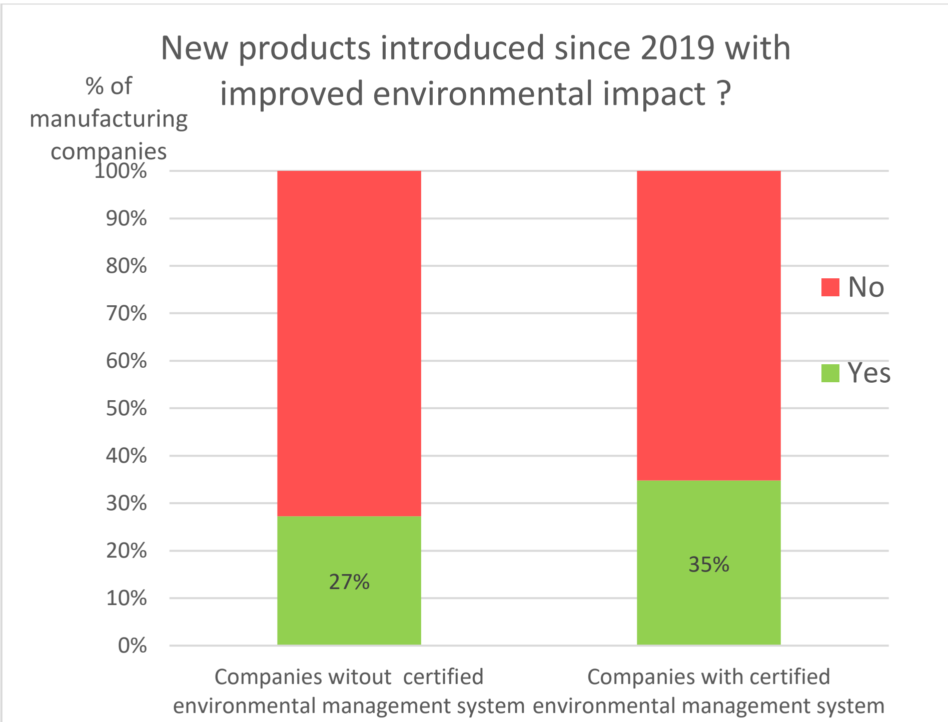

Fig. 6 Environmental Certification and Product Eco-Innovation (calculated from [5])

Firms utilizing Product Lifecycle Management (PLM) systems or Product/Proces Data Management systems are significantly more likely to eco-innovate their new products (55% eco-innovators) than those without such systems (23% eco-innovators) (Fig. 7).

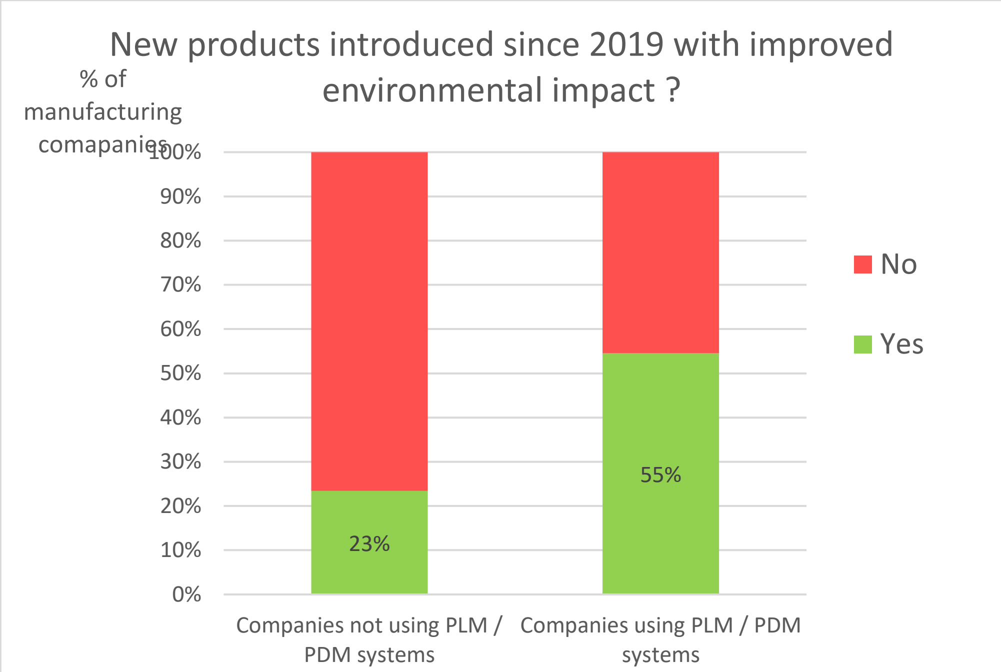

Fig. 7 Use of PLM / PDM Systems and Product Eco-Innovation (calculated from [5])

Firms utilizing Product design simulation software are a bit more likely to eco-innovate their new products (40% eco-innovators) than those without such software (30% eco-innovators) (Fig. 8).

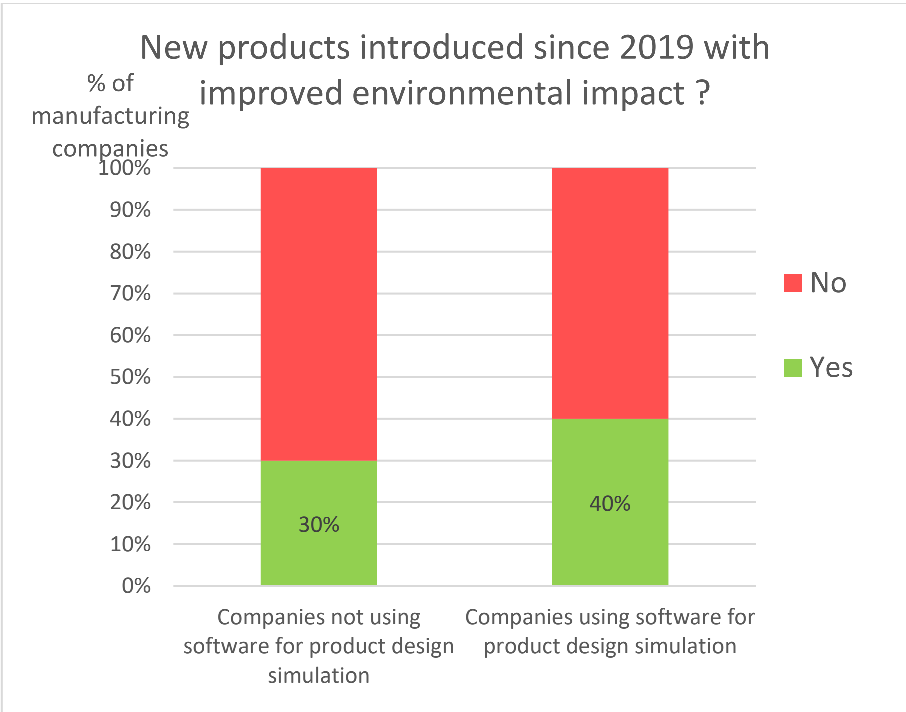

Fig. 8 Use of Product design Simulation Software and Product Eco-Innovation (calculated from [5])

Conclusion

This study reveals a low overall adoption of product eco-innovation among Slovak manufacturing firms. Firm size, R&D activity, employee involvement and training in innovation, and the use of PLM/PDM systems seem to be strong predictors of product eco-innovation in manufacturing companies. Conversely, factors such as environmental certification or using product design simulation software appear not to be impactful.

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POSSIBLE SUPPLY CHAIN RISKS IN ENTERPRISE LOGISTICS

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Abstract: Supply Chain Management (SCM) faces increasing complexity and risks that may disrupt the continuity of production and deliveries. Therefore, risk management has become an essential part of strategic management. The article focuses on identifying and assessing logistical risks in the company Alfa, operating in the automotive industry and applying the “just-in-time” principle. Using systematic analysis, the Ishikawa diagram, and Pareto analysis, the main risks were identified: delayed component deliveries, insufficient communication with suppliers, and limited warehouse capacity. To mitigate these risks, measures such as the implementation of RFID technology, regular audits, and more effective planning were proposed. The results confirm that systematic risk management strengthens the resilience of the supply chain and contributes to the company’s long-term stability and competitiveness.

Keywords: Supply chain management, enterprise logistics, risks

Introduction

In today’s dynamic and globalized environment, supply chain management is becoming increasingly complex and more vulnerable to various risks. Companies are exposed to multiple threats – from disruptions in material flows and unreliable suppliers to unexpected production outages that can seriously affect operational continuity and customer satisfaction. For this reason, risk management in logistics has become a strategic prerequisite for maintaining business stability and competitiveness.

A supply chain encompasses processes related to the flow of raw materials, components, information, and financial resources from the original supplier to the end customer. Its efficiency depends on the interconnection of individual links in the chain and the ability to respond flexibly to unforeseen changes or disruptions [1]. The most common logistics risks include delayed deliveries, damaged goods, lack of storage capacity, technical failures, as well as risks caused by human error or external factors such as geopolitical conflicts, natural disasters, or pandemics.

Effectively addressing these risks requires a systematic approach, including their identification, analysis and assessment, the selection of appropriate methods, and the implementation of corrective measures. Risk management is a process aimed at recognizing, evaluating, and regulating potential adverse events in order to minimize their impact on business objectives [1]. This process consists of several steps – from risk identification and assessment of its likelihood and consequences, through the design of mitigation strategies, to implementation and continuous evaluation of the effectiveness of adopted solutions [2]. The main benefits of effective risk management include reducing uncertainty in decision-making, optimizing processes, saving resources, and strengthening a company’s credibility in the market. On the other hand, the disadvantages are the complexity of calculations, dependence on external data, and high demands on qualified personnel and the implementation of systemic measures [2].

Systematic risk management has thus become an essential part of modern supply chains. Companies that can anticipate, identify, and mitigate risks in a timely manner gain a significant competitive advantage and are able to respond flexibly to the challenges of a turbulent market [3].

The company Alfa, examined in this research, is part of a global technology leader specializing in the development and production of turbochargers for the automotive industry. Its plant in Slovakia plays a key role in the supply chain by ensuring the production and delivery of turbochargers directly to automotive manufacturers (OEMs). The company operates on the principles of just-in-time logistics and uses the SAP R/3 planning system to manage material flows, production, and inventory tracking. Given the high emphasis on accuracy and timeliness, effective risk management and the ability to respond flexibly to problems arising in the supply chain are critically important for the company.

Materials and Methods

For the purposes of this article, various quantitative and qualitative methods were applied to identify, analyze, and classify risks in the logistics processes of the company Alfa. Each tool serves a specific purpose in detecting sources of uncertainty, assessing their severity, and proposing measures to eliminate or mitigate them. The main tools used are as follows:

Systematic risk management analysis

For the purposes of this article, it is important to examine the systematic risk management analysis at the company Alpha which is based on the identification and recording of risks in the CTB MID TERM system. This system, updated weekly, is derived from SAP/R3 data and is used to monitor critical components required for turbocharger production. Component identification is performed by planners, and if a problem cannot be resolved locally, it is escalated to a supervisor or the global quality department.

CTB MID TERM includes the production plan, component delivery dates, inventory-to-demand comparison, customer production schedules, and other key information. Based on this data, risks can be anticipated, missing components identified, and corrective measures proposed, such as transferring stock from another plant, premium air shipments, or rescheduling production. Each planner is responsible for specific suppliers and components, while the company monitors suppliers from Asia, Europe, and America, as well as major customers such as Renault, Audi, and Nissan. The system also includes blocked inventory, problem analysis, responsibilities, and the Red Alert escalation form. Red Alert is used when production or customer delivery is threatened and has four escalation levels, with higher levels triggering global problem-solving through meetings and discussions.

Effective risk management is crucial to ensuring production and delivery continuity, with unpredictable situations minimized through component control and adjustment of supplier contracts. The analysis indicates the following:

1. **Key dependency on deliveries**

•Turbocharger production heavily depends on accurate and timely component deliveries.
•Missing critical components can interrupt production and jeopardize customer deliveries.

2. **Importance of accurate information**

•Production planning is only possible with accurate, up-to-date data on inventory, suppliers, and customer requirements.
•Lack of information or delayed deliveries creates gaps that significantly increase production disruption risk.

3. **Systematic identification and escalation process**

•CTB MID TERM allows weekly identification and tracking of critical components.

•The Red Alert (RAL) system with four escalation levels ensures problems are addressed according to severity – from local measures to global solutions.

4. Flexibility and risk mitigation measures

•The company has prepared solutions: transferring components from other plants, premium air shipments, or rescheduling production.
•Systematic monitoring of inventory, quality, and supplier data helps minimize the impact of unforeseen events.

5. Importance of collaboration and control mechanisms

•Effective risk management requires coordination among planners, production planning, quality, and global management.
•Component control and adjusted supplier contracts are key to ensuring smooth production and customer satisfaction.

Ishikawa Diagram (Cause-and-Effect Diagram)

The Ishikawa diagram, also known as the “fishbone diagram,” enables a systematic identification of the causes of problems or risks that may affect logistics processes. Its advantage lies in its clear visual structure, which groups causes into categories such as people, machines, materials, methods, environment, and measurement. In this study, the diagram was used to map risks impacting the supply chain in the production process [4].

Possible causes influencing risks in the supply chain include:
•incorrect information provided by the supplier,
•delivery delays,
•inventory discrepancies within the company,
•delivery of incorrect quantities of components,
•insufficient quality of supplied parts,
•limited storage capacity,
•inefficient logistics system setup at the port,
•employee errors when ordering materials,
•uncertainty in the component inspection system,
•lack of qualified personnel,
•loss or theft of parts during transport,
•material damage during import,
•incorrectly set delivery dates,
•failure or error in the supplier’s system,
•high rate of defective products in production,
•delayed invoice payments by Alfa.

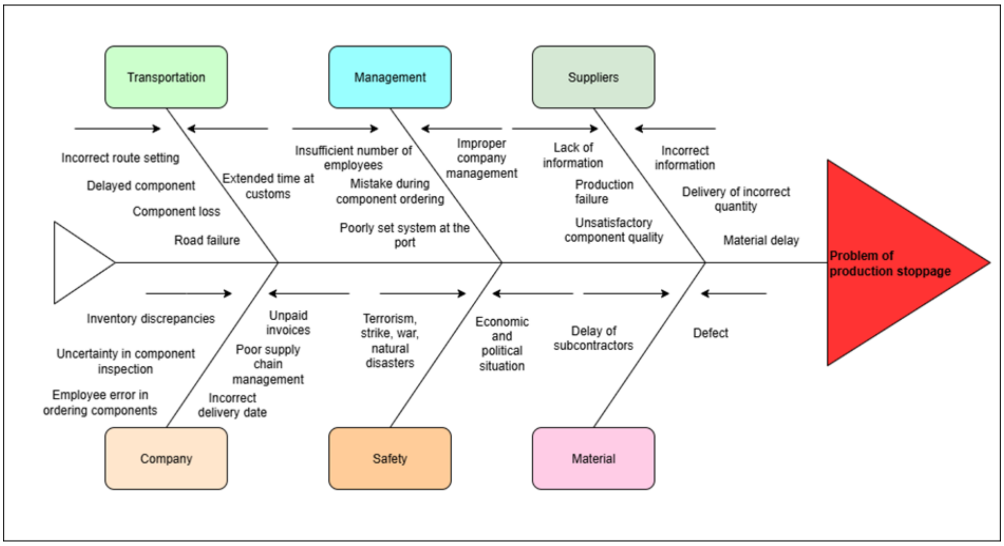

Figure 1 Cause-and-Effect Diagram
References: Author, 2025

Pareto Analysis (80/20 Analysis)

Pareto analysis was used to determine the key risks with the greatest impact on the functioning of the logistics system. With the help of a chart, it was possible to visualize which risk factors occur most frequently or cause the highest damage [5].

In the chart (Figure 2), the main supply chain risks in company Alfa are displayed:

•blue bars represent the severity of individual risks (score × weight),
•the red line shows the cumulative percentage of impact,
•the gray line at 80% marks the threshold beyond which the most critical factors are located.

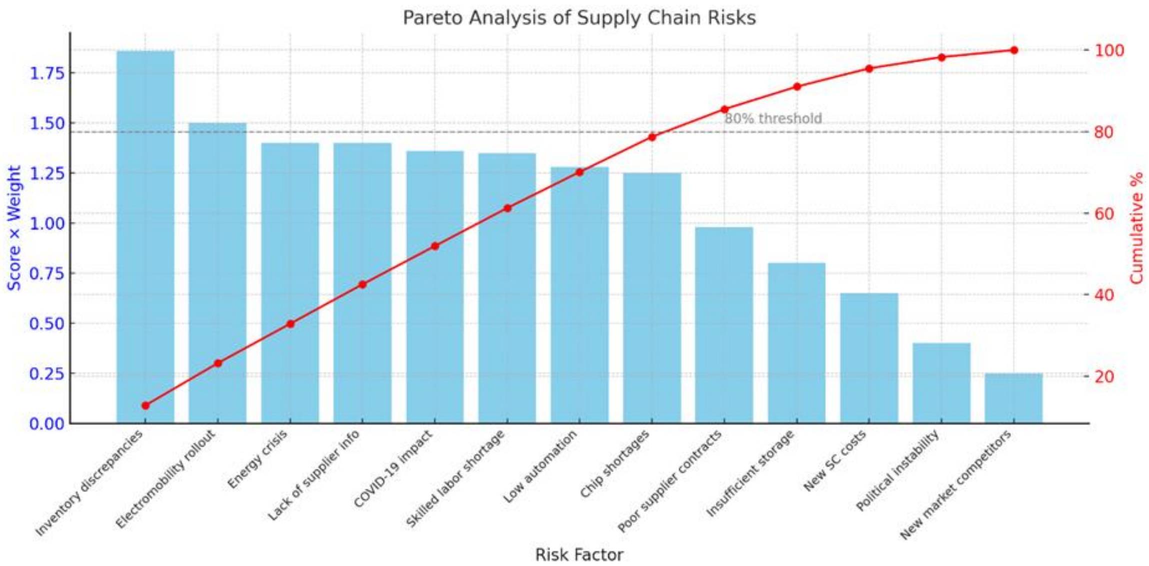

Figure 2 Pareto Analysis of Supply Chain Risks
References: Author, 2025

Among the most critical identified risks, which account for the majority of the total impact, are inventory discrepancies, representing the largest contribution to risk. Another key factor is the rapid rise of electromobility, which creates pressure for production adaptation. The energy crisis significantly increases operating costs and reduces predictability in planning. A lack of information from suppliers limits the company's ability to plan effectively and respond quickly to changes. The COVID-19 pandemic also had a significant impact, causing supply disruptions and reducing production capacity. Furthermore, a shortage of qualified labor decreases the flexibility of the production process. Low levels of automation reduce overall efficiency and increase the likelihood of errors. Another major risk is the shortage of chips, which threatens the smooth continuity of production.

Results

Several analytical tools were used to identify and assess risks. The systematic analysis enabled the identification of areas with a high risk of disruption while also assessing the effectiveness of existing control mechanisms. The analysis revealed that the primary factors influencing risk are delayed deliveries, a lack of accurate information from suppliers, and limited flexibility in production planning. Based on these findings, specific measures were proposed to minimize the risk of production interruptions, including the transfer of components between plants, the use of premium air shipments, and adjustments to the production schedule.
The second was the Ishikawa diagram, which was applied to the production area and allowed for a systematic breakdown of the causes of potential problems in the supply chain. Among the most critical causes identified through the diagram were delivery delays, insufficient quality control of components, machine breakdowns, and human errors. These factors directly increase the risk of production interruptions and disruption of deliveries to customers.
The results of the Pareto analysis indicated that the largest portion of overall risk stems from potential production stoppages due to delayed component deliveries, followed by insufficient warehouse capacity and weak communication with subcontractors. These three areas represent key priorities, as they account for approximately 80% of all identified impacts. Recommended solutions include optimizing warehouse capacity and carefully planning the delivery of critical components.
Based on the identified and analyzed risks in the supply chain of company Alfa, specific measures were proposed to eliminate or mitigate their negative impact on logistics flow and production continuity (Table 1). In the technological area, the implementation of RFID gates at critical warehouse and production points is recommended. In addition to technological solutions, it is advised to introduce regular internal risk audits and employee training in logistics risk management. Finally, the creation of an integrated reporting tool is recommended, which would consolidate outputs from analyses, risk matrices, Red Alerts, and audits into a single, clear visualization. The goal of this tool is to provide management with a comprehensive overview of current risks, their development, and the measures taken.

Tab. 16 Identified risks and proposed measures

Identified Risks	Proposed Measures
Delayed component deliveries	Careful planning of critical component deliveries
Lack of accurate information from suppliers	Implementation of RFID gates at critical warehouse and production points
Limited flexibility in production planning	Employee training in logistics risk management
Human errors	Creation of an integrated reporting tool
Insufficient quality control of components	Transfer of components between plants

Conclusion

The aim of this article was to identify risks in the supply chain of company Alfa, analyze them using selected tools, and propose specific solutions for their mitigation. Tools such as the systematic analysis, Ishikawa diagram and Pareto analysis were employed, enabling a systematic and multi-dimensional view of logistics risks and their impact on business operations. The analysis confirmed that the most significant risks include delayed delivery of components, technical failures in production, and the accumulation of problems, all of which can directly threaten production and delivery continuity. This has a major impact on reputation and financial performance in the automotive industry. The proposed measures focus on strengthening response mechanisms (e.g., improving the Red Alert system), increasing transparency through RFID technology, diversifying supply channels, and enhancing analytical capabilities in risk management. By implementing these solutions, the company can significantly increase its resilience to supply chain disruptions and gain a stable logistical advantage.

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INTEGRATED APPROACH TO EVALUATING THE ECONOMIC EFFICIENCY AND RISK OF AN INVESTMENT PROJECT

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Abstract: The paper presents a comprehensive procedure for deciding on the implementation of an investment project in the construction industry. The procedure is processed in two steps. First, the economic efficiency of a real investment project is assessed using dynamic financial criteria in terms of profitability and liquidity. Subsequently, the risk is analyzed using the Monte Carlo simulation method using the Crystal Ball software tool. The result is a decision to implement or not to implement an investment project.
Keywords: Investment, economic efficiency, risk, simulation, Monte Carlo method.

Introduction

Investment decision-making is a key element of strategic management of enterprises, especially in an environment of increasing uncertainty, pressure for efficiency and limited resources. Dynamic methods of assessing the economic efficiency of investment projects – such as Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI) or Discounted Payback Period (DPP) – provide a basic framework for assessing the financial feasibility of projects. [2, 4] However, these approaches in most cases assume deterministic inputs and therefore do not take into account the variability of economic parameters or the impact of risk scenarios on the resulting efficiency of the project.

For this reason, an integrated approach that combines deterministic methods with risk quantification tools has been increasingly promoted in recent years. The most important of these is the Monte Carlo method, which allows for the analysis of a wide range of possible outcomes through simulations and the probabilistic estimation of the impacts of uncertainty on the economic efficiency of an investment. [1, 3]

Investment activity is associated with a high level of risk and uncertainty. Failures of investment projects often result from overestimated expectations, inaccurate estimates of capital and operating costs, or underestimation of risks associated with the implementation and operational phase of the project. An integrated approach thus represents a necessary step towards a more realistic and comprehensive assessment of investment intentions, which enables better decision-making in the conditions of digital transformation and dynamically changing markets.

The aim of the paper is to present methodological starting points and practical possibilities for using an integrated approach to assessing the economic efficiency and risk of investment projects, with an emphasis on the application of the Monte Carlo method as a tool for supporting decision-making in the corporate investment process.

Methods and methodology

The subject of the solution is a development investment project focused on the procurement of a road milling machine. The reason for the procurement of a road milling machine is the fact that the construction company is faced with several operational challenges, which include mainly the seasonality of construction work, increasing costs of materials and energy, a lack of qualified labor, as well as dependence on the rental of specialized construction equipment. If the company does not procure its own equipment, it will be forced to ensure its availability by renting it from external suppliers, which is associated with significantly higher costs and operational risks (e.g. limited availability of equipment during the season, dependence on the lessor's schedule, etc.). Decision-making on the investment project is carried out in two steps. The first step involves a quantitative assessment of the economic efficiency of the investment in terms of its profitability using the financial criteria NPV, IRR, PI and liquidity (return) using the financial criterion DPP. The calculation of the above financial criteria is based on the expected annual cash flows from operation over the economic life of the road milling machine (6 years). This is a deterministic approach. The basic input data are recorded in Tab. 1.

Tab. 1 Input data for calculating the economic efficiency of an investment project

Input variable	Unit	Value
Cost of the cutter	EUR	600,000
Annual depreciation	EUR/year	100,000
Number of days the cutter is used for own orders	days/year	100
Number of days of commercial rental	days/year	20
Lease price	EUR/day	2,500
Savings from replacing rental with own equipment	EUR/year	250,000
Commercial rental income	EUR/year	50,000
Labor costs	EUR/year	54,000
Fuel costs	EUR/year	57,750
Maintenance costs	EUR/year	17,000
Equipment insurance costs	EUR/year	200
Discount rate	%	4.97

Source: Own processing

Calculations of the economic efficiency of the investment are carried out for:

- Scenario A, which is without additional income - includes only the rental savings, since the use of the milling machine is only for own orders.
- Scenario B, which is with income - includes, in addition to the savings from the rental, the commercial use of the milling machine, and possibly also income from the sale of the asphalt mixture.

In the second step, the investment is assessed in terms of risk using the Monte Carlo method, which allows quantifying the impact of individual risk factors (input variables) on the output value NPV through stochastic modelling. When creating a simulation model, it is necessary to choose an appropriate type of probability distribution for the risk factors. The choice of probability distribution itself is based on the nature of the input variable, the availability of historical or expert data, and the nature of the fluctuation of observed or expected values. In this case, three probability distributions are used for individual input variables:

- BetaPERT distribution – expected number of days per year, cost of renting a cutter, labor costs, fuel costs.
- Uniform distribution – expected number of days of bad weather per year, technical downtime, logistics (movements), coordination in construction, internal use of the cutter, commercial rental of the cutter in days per year, fuel consumption, equipment insurance costs.
- Triangular distribution – equipment maintenance costs.

Each risk input variable defined in this way becomes a stochastic variable and, based on Monte Carlo simulation, it is possible to quantify the impact of its variability on the monitored output variable NPV. The number of simulations is 100,000.

Results of economic efficiency of an investment project – deterministic approach
The assessment of the economic efficiency of an investment project is carried out using the dynamic financial criteria listed in Tab. 2.

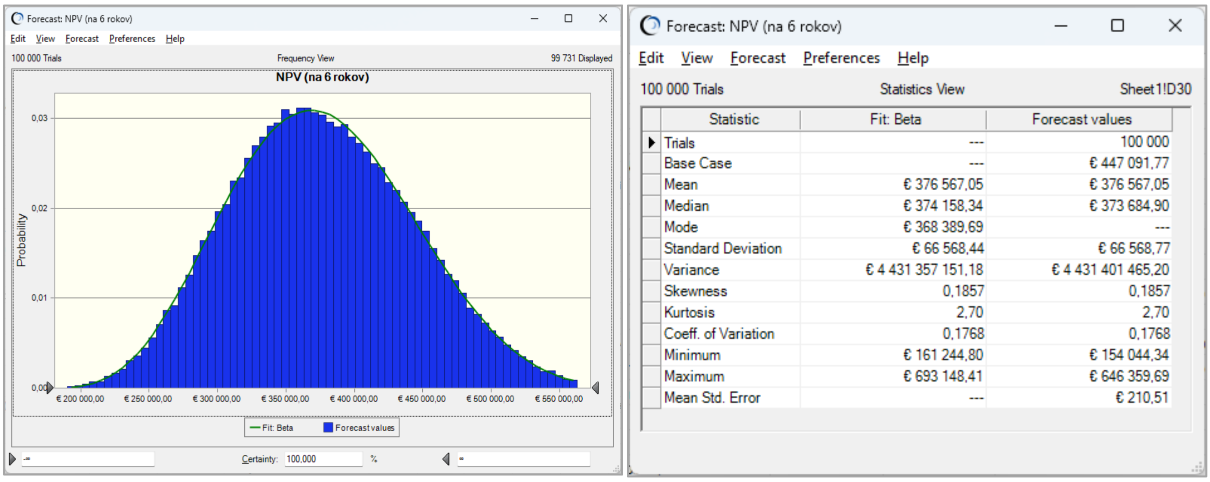
Tab. 2 Economic efficiency of an investment project using dynamic financial criteria

Financial criterion	Unit	Scenario A (without income)	Scenario B (with income)	Investment acceptance condition
Net Present Value (NPV)	EUR	447,091.77	648,935.12	NPV > 0
Profitability Index (PI)	coefficient	1.75	2.08	PI > 1
Internal Rate of Return (IRR)	%	27.77	34.07	IRR > WACC
Discounted Payback Period (DPP)	years	3.23	2.68	DPP < 6 years

Source: Own processing

In both scenarios, the basic conditions for the acceptability of the investment according to the individual financial criteria were met. The NPV generates a positive added value at a real discount rate of 4.79 %. The IRR values of 27.76 % (in scenario A) and 34.07 % (in scenario B) significantly exceed the weighted average cost of capital (WACC = 4.79 %), which signals the ability of the investment to generate an above-average return and absorb any increase in capital costs. The IP values of 1.75 (in scenario A) and 2.08 (in scenario B) confirm that the return on each invested euro exceeds its value. The index expresses the efficient use of capital and supports the decision to implement the project. The DPP reaches a value of 3.23 years (in scenario A) and 2.68 years (in scenario B), which means that the investment will be repaid before the end of its planned lifetime. A shorter payback period reduces investment risk and increases the predictability of future cash flows.
The differences between scenarios A and B show that the savings from leasing the investment alone are sufficient to return the investment, albeit with a longer time horizon and less margin for changes in input parameters. Conversely, including additional income from leasing the investment leads to a significant improvement in all monitored indicators and confirms the potential of the project to create value even under more challenging financing conditions.

Results of risk analysis of an investment project using the Monte Carlo method
Risk analysis using the Monte Carlo method allows modelling the uncertainty of input variables and generating a probability distribution of the output quantity, namely NPV. The simulation model is implemented in the Microsoft Excel environment using the Crystal Ball software tool. The simulation results in a comprehensive risk assessment, including an analysis of the sensitivity of risk variables to the resulting investment value, which provides a more realistic picture of the potential return on the project under conditions of variability and uncertainty.
The evaluation of statistical data (Fig. 1) and their subsequent adjustment by Beta distribution confirm that the project is stable, economically viable and resistant to common operational risks. The behavior of the results within the simulation is logical, realistic and appropriately modelled, which increases confidence in the quality of the investment analysis.



Statistic	Fit: Beta	Forecast values
Trials	---	100 000
Base Case	---	€ 447 091,77
Mean	€ 376 567,05	€ 376 567,05
Median	€ 374 158,34	€ 373 684,90
Mode	€ 368 389,69	---
Standard Deviation	€ 66 568,44	€ 66 568,77
Variance	€ 4 431 357 151,18	€ 4 431 401 465,20
Skewness	0,1857	0,1857
Kurtosis	2,70	2,70
Coeff. of Variation	0,1768	0,1768
Minimum	€ 161 244,80	€ 154 044,34
Maximum	€ 693 148,41	€ 646 359,69
Mean Std. Error	---	€ 210,51

Fig. 1 NPV probability distribution and its statistical characteristics
Source: Own processing

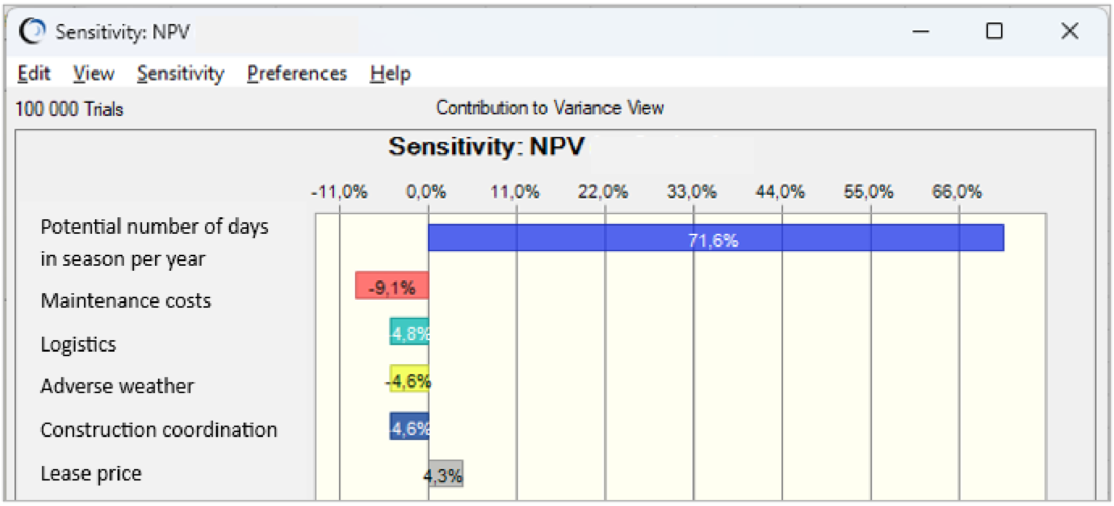


Fig. 2 NPV sensitivity chart
Source: Own processing

The NPV sensitivity chart (Fig. 2) documents that the greatest impact on the success of the investment project is caused by factors related to the efficient use of working days, especially the number of days in the season, logistical transfers, adverse weather and construction coordination. Conversely, factors such as maintenance costs and organizational downtime (logistics, weather, construction coordination) have a negative impact on the investment performance by reducing machine availability and limiting revenue generation. Other costs, such as employee wages, fuel consumption or annual insurance, have a negligible impact on the NPV within the model and their optimization is of limited importance from the perspective of the overall project profitability.

Conclusion

The results of the economic efficiency assessment of the investment project confirm that the investment in the acquisition of its own road milling machine is financially feasible and effective in terms of profitability and liquidity - return. The project has strong potential to generate profit and represents a suitable investment opportunity even with higher capital costs or slightly adverse conditions.

Sensitivity analysis of the output value NPV carried out using the Monte Carlo simulation method confirms that the success of the investment is primarily determined by operational planning and the ability to minimize losses of effective working time. Management recommendations should focus mainly on maximizing the number of effective working days, optimizing logistics and construction coordination, and on effective technical management of the facility in order to minimize maintenance costs. By implementing these measures, it is possible to significantly reduce the variability of results and ensure a stable return on investment. The results of the analysis show that the impact of risk factors caused a decrease in the net present value of the project by EUR 70,524.72, from the original EUR 447,091.77 to EUR 376,567.05.

The contribution was addressed within the projects KEGA 038TUKE-4/2024, KEGA 019TUKE-4/2025 and VEGA 1/0219/23.

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APPLICATION OF THE TPM METHOD IN PRODUCTION AND MAINTENANCE PROCESSES IN A SELECTED COMPANY

Andrea SEŇOVÁ – Annamária BEHÚNOVÁ

Abstract: The article focuses on the application of the Total Productive Maintenance (TPM) method in the conditions of a mining company – the Trebejov quarry. The main objective is to analyse the failure rate of mobile and stationary equipment in 2024 and, based on the findings, propose practical measures to reduce downtime, increase reliability and support more efficient maintenance management. The proposed measures are based on the pillars of TPM (autonomous maintenance, planned maintenance, training) and the 5S method.

Keywords: TPM, 5S, Autonomous maintenance, Mobile devices, Stationary devices.

Introduction

In today's competitive environment, any production depends on its efficiency. The efficiency of the production process is one of the main goals of every company. Production can be increased efficiently by ensuring that the production process is continuous. This means that the equipment is in good technical condition and therefore without downtime. Preventive maintenance helps to avoid these unexpected downtimes, reducing the cost of repairing machinery and equipment and eliminating the risk of breakdowns and subsequent production losses.

It is very important to highlight the importance of preventive and productive maintenance and its impact on the production process. One of the tools for this maintenance is the application of the TPM (Total Productive Maintenance) system, which brings about a complete change in the approach to maintenance. The aim is to provide a broader overview of the benefits and application of TPM with an emphasis on its practical use in a business environment. Through analysis and proposals, we seek to highlight the importance of TPM as a strategic tool for achieving sustained competitiveness and sustainable growth for businesses in today's competitive environment. We looked at how the systematic implementation of TPM can contribute to the efficiency of a company's performance. Is it, for example, a reduction in downtime, an increase in production quality, cost optimisation or improved safety at work? We also analysed the challenges and obstacles that a manufacturing company may encounter when applying TPM. The aim of the paper was to develop 5S standards and simple instructions for the primary stone processing line in terms of the TPM system, which is one of the tools of preventive maintenance. We analysed the existing list for mobile and stationary equipment in 2024 and proposed the necessary measures to reduce failures.

Literature review

The production process is a set of interconnected activities that transform inputs – such as raw materials, energy, information and human labour – into outputs in the form of final products or services. The efficiency of production processes is determined by the level of organisation, the quality of equipment and maintenance, which has a fundamental impact on their reliability and productivity [7]. Maintenance according to the STN EN 13306:2018 standard includes all technical, administrative and managerial activities during the life cycle of equipment, the aim of which is to maintain or restore its functional condition [9].

Currently, the trend in manufacturing companies is to focus on lean management, which aims to eliminate losses, inefficient activities and waste. The key pillars of the lean philosophy are the Kaizen, Kanban, Six Sigma, 5S and 5 Why methods, which together support continuous improvement in performance and quality [1].[7]. Kaizen, as a philosophy of small steps, aims to involve all employees in the improvement process. Kanban serves as a visual system for managing the flow of work and materials, contributing to smooth production and reducing inventory [8]. The Six Sigma method uses statistical tools to analyse quality and reduce variability in production processes through the DMAIC cycle – define, measure, analyse, improve and control [5].

The 5S method (Seiri – sorting, Seiton – organising, Seiso – cleaning, Seiketsu – standardising, Shitsuke – discipline) is a fundamental step towards ensuring an efficient, safe and visually organised workplace. The implementation of 5S in practice creates the conditions for the effective functioning of the TPM system, as it eliminates unnecessary movements, reduces maintenance time and improves the clarity of the working environment [10].

Based on these principles, method TPM was developed, which represents a comprehensive system of care for production equipment with the aim of achieving zero breakdowns, zero losses and zero accidents [3][6]. TPM combines production, maintenance and management into a single framework and ensures the active involvement of all employees – from operators to company management. The aim is not only to repair equipment after a breakdown, but above all to prevent breakdowns through regular inspections and planned maintenance. The basic principles of TPM are based on eight pillars that ensure the long-term effectiveness of the system: autonomous maintenance, planned maintenance, quality management, training and skills development, early equipment management, process improvement, safety and environmental protection, and the application of TPM in administration [2][8][11]. In practical terms, an important outcome of these pillars is a reduction in the number of breakdowns and downtime, increased equipment reliability and more efficient use of maintenance working time. In the company under review, the TPM system is part of the internal Carmeuse Management System (CMS) framework. This system includes visual management using coloured TPM cards (red, green, blue), zoning of workplaces (A – quarry, B – production line, C – maintenance) and systematic evaluation of faults during regular maintenance meetings [3][4][8]. The aim of this approach is not only to increase the technical reliability of equipment, but also to develop employee awareness of fault prevention, improve communication between maintenance and production, and create a culture of responsibility for the technical condition of equipment. From a theoretical point of view, TPM can therefore be considered a comprehensive system for managing the performance of production equipment, integrating the Lean philosophy, the 5S methodology and the principles of participatory management. Its aim is to strengthen the bond between man and machine, eliminate hidden losses and create conditions for long-term sustainable and safe production [3][6][7].

Methods and methodology

The methodology used is based on the **Total Productive Maintenance (TPM)** concept applied in mining companies. In this article, we used the following methodological procedure:

1. **Division of workplaces into TPM zones:**
    - **Zone A – quarry**, where the condition of mobile equipment and its daily inspections are monitored

  - **Zone B – production line**, focused on stationary equipment (crushers, sorters, belts),
  - **Zone C – maintenance**, where repairs are carried out, TPM cards are recorded and preventive plans are kept.
2. **TPM card system:**
   - **Red card** – urgent or safety fault,
   - **Green card** – fault resolved by maintenance,
   - **Blue card** – fault resolved directly by the equipment operator.
3. **Pillars of the TPM method:**
   - autonomous maintenance,
   - planned maintenance,
   - process improvement,
   - quality,
   - safety,
   - employee skills development.
4. **Method objective:** to achieve **zero breakdowns and zero losses** through the full involvement of employees in equipment maintenance.
5. **Underlying data for analysis:** internal records of breakdowns for 2024, which were processed into summary tables and used to identify the most failure-prone groups of equipment.

Results and Discussion

Analysis of mobile equipment failures

Mobile mechanisms (CAT 980 XE, KOMATSU WA 380, dump trucks) ensure the flow of material from the quarry to the line. In 2024, a total of 13 faults were recorded on four mobile devices, with the most frequent faults occurring on the CAT 980 XE loader (6 faults). From a TPM perspective, it is important to note that most of the faults were detected during daily inspections by operators and were not sudden breakdowns, but rather a gradual deterioration in condition – leaks, wear and tear, rear-view mirror heating faults and oil leaks.

Table 1 Troubleshooting for mobile equipment

Number	Type	Condition	Detected	Device
1	Fault	CLOSED	Maintenance	KOMATSU dumper no. 2
2	Fault	CLOSED	Maintenance	CAT 980 XE loader
3	Fault	CLOSED	Maintenance	KOMATSU WA380 loader
4	Fault	CLOSED	Maintenance	KOMATSU WA380 loader
5	Fault	CLOSED	Maintenance	CAT 980 XE loader
6	Fault	CLOSED	Maintenance	KOMATSU Dumper No. 2

7	Fault	CLOSED	Maintenance	CAT 980 XE loader
8	Fault	CLOSED	Maintenance	KOMATSU WA380 loader
9	Fault	CLOSED	Maintenance	KOMATSU Dumper No. 1
10	Fault	CLOSED	Maintenance	CAT 980 XE loader
11	Fault	CLOSED	Maintenance	KOMATSU Dumper No. 1
12	Fault	CLOSED	Maintenance	CAT 980 XE loader
13	Fault	CLOSED	Maintenance	CAT 980 XE loader

Table 2 Troubleshooting for mobile devices

Number	**Date of entry**	**Method of fault detection**	**Fault description**
1	24.1.2024	Daily inspection	Right rear-view mirror – heating not working
2	24.1.2024	Daily inspection	Temporary repair of central pin lubrication – permanent repair required, restoration of automatic lubrication
3	29.1.2024	Daily inspection	L01 CA 428 – engine system failure
4	21.3.2024	Inspection	Worn front side blades of the bucket – rotate by 180°
5	26.3.2024	Daily inspection	Oil leak from hydraulic lines under the cab
6	25.4.2024	Daily inspection	Broken lower small rear-view mirror on ĽS
7	30.4.2024	Daily inspection	Damaged central lubrication hose on LS under the shovel
8	18.6.2024	Daily inspection	Poor air conditioning efficiency
9	6.8.2024	Daily inspection	L04 CA 1117 – engine system failure
10	9.9.2024	Daily inspection	Brake disc scrub
11	31.10.2024	Daily inspection	Starts up to 3–4 times
12	4.11.2024	Daily inspection	Side boom pin missing

13	6.11.2024	Daily inspection	Worn bucket teeth

Table 3 Troubleshooting for mobile equipment

Priority	**Requested date of removal**	**Who will fix it**	**Date of repair**
6 - SAFETY	February 2024	External company – service	5 March 2024
3 - urgent request	February 2024	External company – service	16 February 2024
3 – urgent request	Week 19, 2024	External company – service	13 May 2024
3 – urgent request	Week 25, 2024	External company – service	8 July 2024
3 - urgent request	ASAP	External company – service	7 August 2024
3 - urgent request	Week 37, 2024	External company – service	24 September 2024
3 - urgent request	November 2024	External company – service	14 November 2024
3 - urgent request	Week 45, 2024	Machinery maintenance	4 November 2024
3 - urgent request	November 2024	Machinery maintenance	27

Table 4 Faults on mobile devices

Device	**Number of faults**	**Average duration of failure**	**Production stoppage**	**Max duration**	**Minimum duration**
CAT 980 XE loader	6	18 days	2 days	23 days	1 day
KOM WA 380 loader	3	21 days	No	35 days	7 days
KOM 2 dumper	2	41 days	No	31 days	5 days
KOM 1 dumper	2	8 days	3 days	15 days	1 day

In 2024, there were a total of 13 faults on four mobile devices (see Table 4). The faults were repaired by both internal and external maintenance. In terms of impact on production, the CAT 980 XE loader (2 days of production stoppage) and the KOM 1 dumper (3 days of production stoppage) were critical. The scope of service intervention priorities is shown in Table 4.

Analysis of stationary equipment failures

In 2024, stationary equipment on the production line was more prone to failure than mobile equipment, with a total of 70 faults recorded. Belt conveyors required the most interventions (25 units, with a total length of almost 2 km), with up to 46 faults recorded. These failures were mostly minor (roller replacement, belt adjustment), but in two cases the belt broke and it was necessary to call in a supplier, which caused an unplanned production shutdown for 9 days.

Table 5 Analysis of stationary equipment failures in 2024

Equipment group	Number of failures/deficiencies	Unplanned downtime	Note
Crushers (primary, tertiary)	7	4 days	Replacement of segments, reconstruction of parts of the treatment plant
Sorters (MOGENSEN SR 5230)	repeatedly	3 days	replacement of damaged screens during sorting 0–4 mm
Belt conveyors (25 pcs)	46	9 days	belt tear, other faults repaired within a day
Other equipment	rest up to 70	–	quickly remedied, no impact on production

With a planned daily production of 1,750 tonnes, 14 days of unplanned downtime means a loss of 24,500 tonnes, which is approximately 7% of the annual production of 350,000 tonnes. TPM must therefore focus primarily on equipment with a high frequency of faults, especially belt conveyors.

Proposed measures according to TPM and 5S

- Identify and maintain a minimum stock of the most frequently used spare parts for mobile and stationary equipment;
- Shorten the response time of external service companies by agreeing on a fixed intervention deadline;
- Replace missing maintenance workers (the report indicates a shortage of 2 qualified maintenance workers);
- Evaluate faults monthly according to the table and change the frequency of preventive maintenance according to the actual situation;
- Identify the most frequently used spare parts and set minimum stock quantities (mobile and stationary);
- Introduce more frequent preventive maintenance on faulty equipment (autonomous + planned maintenance);
- Train operators to identify and immediately report deviations (TPM cards, visual management).
- Review SLAs with service partners to reduce the time from reporting to intervention (priority "3 - urgent request", "6 - SAFETY");
- Develop simple instructions and 5S standards for key workplaces (crusher, sorter, belts);
- Introduce OEE measurement for key nodes of the primary line and use daily/monthly comparisons.

The SLA would stipulate that the service company must respond within 8 hours of a crusher malfunction being reported and complete the repair within 24 hours, otherwise a penalty will be applied. OEE is used as the main indicator for monitoring the results of TPM implementation – improvements in autonomous and planned maintenance should lead to an increase in OEE of 5–10% over the course of a year. The application of TPM in the quarry shows that the mere introduction of fault recording, division into zones and working with coloured cards leads to better discipline in maintenance. However, it is crucial that the data from the tables is further processed and that maintenance plans are changed accordingly – otherwise, TPM will remain only a formal tool. The combination of visual management (TPM cards), standardisation (5S) and efficiency measurement (OEE) will reduce response times and prevent reactive repairs. It is essential to support autonomous maintenance so that operators perform daily checks (cleaning, tightening, lubricating, checking for leaks) and record deviations in cards/CMMS.

Conclusion

TPM is a complex of activities that allows you to manage, organise and efficiently organise the maintenance process not only in mining operations, but in any industrial sector. Mastering this management system allows you to quickly identify deficiencies and malfunctions and then track their elimination with precise timing and employee responsibility for their elimination. The TPM process requires the involvement of all company employees, as production initially reports the deficiency, maintenance eliminates it, purchasing secures replacement parts, the finance department evaluates the total cost of the repair, and the occupational safety department evaluates the risks. In total, there are more than 150 5S standards and simple instructions (Simple Instruction) in the quarry. The information is processed in the form of catalogue sheets, which are placed in the workplaces and employees have the opportunity to review them on a daily basis. By analyzing and monitoring work in the quarry, we found that the system was not being used comprehensively. After its introduction in 2018, individual parts of the process, such as the 5S standard and simple instructions, were not updated. It was therefore necessary to focus on updating these documents on the primary line of the quarry processing plant. The 2024 analysis confirmed that the greatest benefits of TPM will be achieved on mobile and stationary equipment. The proposed measures, in line with the pillars of TPM and 5S, create the conditions for reducing unplanned downtime, shortening service times and improving maintenance planning. Implementation requires discipline, training and ongoing measurement of results. The TPM process should never be interrupted; it should continue, improve and be refined. All stakeholders should learn from their results and analyses, draw conclusions that will lead to fewer breakdowns and faster repairs in the future, which ultimately leads to higher production performance and growth in the economic results of the operation.
This system is particularly advantageous for multinational companies where the same technology or similar equipment is used, as it allows for comparison of the effectiveness of repairs in individual plants.

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