ŽILINSKÁ UNIVERZITA V ŽILINE
STROJNÍCKA FAKULTA
KATEDRA PRIEMYSELNÉHO INŽINIERSTVA

and

UNIWERSYTET BIELSKO-BIALSKI
WYDZIAŁ BUDOWY MASZYN I INFORMATYKI
KATEDRA INŻYNIERII PRODUKCJI

Katedra priemyselného a digitálneho inžinierstva, Technická univerzita v Košiciach
Katedra biomedicínskeho inžinierstva a merania, Technická univerzita v Košiciach
Katedra kvality, bezpečnosti a environmentu, Technická univerzita v Košiciach
Ústav priemyselného inžinierstva a manažmentu, Slovenská technická univerzita v Bratislave
Katedra výrobných technológií a manažmentu kvality, Technická univerzita vo Zvolene
Katedra informatyzacji i robotyzacji produkcji, Politechnika Lubelska
Katedra průmyslového inženýrství a managementu, Západočeská univerzita v Plzni
Katedra managementu kvality, Vysoká škola báňská - Technická univerzita Ostrava

INVENTION FOR ENTERPRISE

InvEnt 2025

KATEDRA PRIEMYSELNÉHO INŽINIERSTVA
STROJNÍCKA FAKULTA
ŽILINSKÁ UNIVERZITA V ŽILINE

and

UNIWERSYTET BIELSKO-BIALSKI
WYDZIAŁ BUDOWY MASZYN I INFORMATYKI
KATEDRA INŻYNIERII PRODUKCJI

Katedra priemyselného a digitálneho inžinierstva, Technická univerzita v Košiciach
Katedra biomedicínskeho inžinierstva a merania, Technická univerzita v Košiciach
Katedra kvality, bezpečnosti a environmentu, Technická univerzita v Košiciach
Ústav priemyselného inžinierstva a manažmentu, Slovenská technická univerzita v Bratislave
Katedra výrobných technológií a manažmentu kvality, Technická univerzita vo Zvolene
Katedra informatyzacji i robotyzacji produkcji, Politechnika Lubelska
Katedra průmyslového inženýrství a managementu, Západočeská univerzita v Plzni
Katedra managementu kvality, Vysoká škola báňská – Technická univerzita Ostrava

INVENTION FOR ENTERPRISE

InvEnt 2025

16. – 18. 6. 2025, Štrbské Pleso

Proceedings
of the Scientific International Conference
InvEnt 2024

Editor-in-chief: Assoc. Prof. Ing. Martin Gašo, PhD.

Scientific Committee

Proceedings
of the Scientific International Conference
InvEnt 2024

Editor-in-chief: Assoc. Prof. Ing. Martin Gašo, PhD.

Reviewers

Assoc. Prof. Ing. Helena Fidlerová, PhD.
Assoc. Prof. Ing. Juraj Kováč, PhD.
Assoc. Prof. Ing. Erika Sujová, PhD.
Assoc. Prof. Ing. Marek Šolc, PhD.
Assoc. Prof. Ing. Marianna Tomašková, PhD.
Assoc. Prof. Ing. Renáta Turisová, PhD.
dr inż. Wojciech Danilczuk
dr inż. Elżbieta Doluk
dr inż. Jakub Pizoń
dr inż. Jakub Szabelski
Ing. Mária Homokyová, PhD.
Ing. Martina Horváthová, PhD.
Ing. Zuzana Kotianová, PhD., MBA
Ing. Mgr. Jana Kronová, PhD.
Ing. Jana Mesárošová, PhD.
Ing. Marek Mizerák, PhD.
Ing. Jozef Trojan, PhD.
Ing. Jaroslava Szabó

All articles in the proceedings were reviewed of two reviewers.
The articles have not undergone editorial, graphic or language treatment.

Organising Committee

Chairman of the Organising Committee: Assoc. Prof. Ing. Martin Gašo, PhD.

prof. Ing. Ľuboslav Dulina, PhD.
dr inż. Sławomir Kukla
dr inż. Dorota Więcek
dr inż. Dariusz Więcek
Ing. Marián Matys, PhD.
Ing. Tomáš Balala
Ing. Martin Buzalka
Ing. Dávid Komačka
Ing. Dana Lošonská
Ing. Milan Marčan
Ing. Lucia Mozolová
Ing. Andrej Polka
Ing Ján Zuzik

Organisational guaranty of the conference

UNIVERSITY OF ŽILINA
Faculty of Mechanical Engineering

Department of Industrial Engineering

KIP

HARA n. o.

Title:	InvEnt 2025 Industrial Engineering – Invention for Enterprise
Kind of publication:	Proceedings
Publisher:	Fundacja Centrum Nowych Technologii
Date of issue:	June 2025
Proceedings makers:	Ing. Andrej Polka
Cover and Design:	Assoc. Prof. Ing. Martin Gašo, PhD.
Editor-in-chief:	Assoc. Prof. Ing. Martin Gašo, PhD.
Edition:	1st Edition
Range:	104 Pages
Link:	www.priemyselneinzinierstvo.sk
Font:	Arial
e-Book	ISBN 978-83-947909-9-8 www.priemyselneinzinierstvo.sk https://kip.ubb.edu.pl/

Content

Content

Tomáš BALALA[1], Branislav MIČIETA[2], Martin GAŠO[3]

USING VIRTUAL REALITY AS AN INNOVATIVE TOOL IN KAIZEN WORKSHOPS

Abstract

The article discusses virtual reality (VR) as an innovative tool for Kaizen workshops aimed at continuous improvement of business processes. It introduces Kaizen philosophy and the limits of traditional workshops. It discusses the history and possibilities of VR technologies. The main part describes the implementation of VR in the different phases of the workshop. The results point to possible efficiency gains, cost reductions and higher participant engagement.

Key words: virtual reality (VR), Kaizen workshop, business process improvement, simulation of production processes.

1. INTRODUCTION

Business progress has evolved significantly since the mid-20th century. After the Second World War, quality management focused on product characteristics. In the 1970s, the focus shifted to manufacturing processes. In the 1980s and 1990s, Lean and Six Sigma methodologies proliferated. The former focuses on eliminating inefficient activities, the latter uses statistical tools to reduce errors [1,2].

In this context, the philosophy of Kaizen, or 'continuous improvement,' emerged and became the basis for the rebuilding of Japanese industry after the war. Kaizen workshops, which are short-term, intensive activities aimed at rapid improvement of specific processes using multidisciplinary teams, are used to implement their principles [3,4].

These workshops are now enriched by virtual reality (VR), which originated in the 1960s. From mechanical devices such as the "Sensorama", VR technology has evolved to become an accessible simulation of work environments, used in design, training and coaching.

---

[1] Tomáš Balala, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, tomas.balala@fstroj.uniza.sk
[2] Branislav Mičieta, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, branislav.micieta@fstroj.uniza.sk
[3] Martin Gašo, assoc. prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, martin.gaso@fstroj.uniza.sk

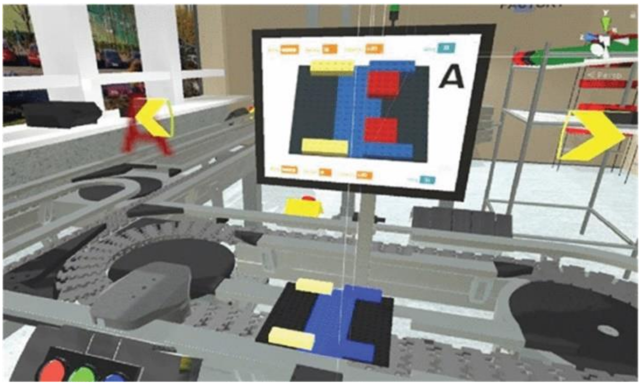


Fig. 1. View of the VR application at workplace [5]

VR now allows visualization and interaction with digital models workplaces(fig 1.) without disrupting real production, thus increasing the effectiveness of training sessions [5,6].

2. LITERATURE REVIEW

The link between virtual reality (VR) and process improvement methods such as Kaizen workshops is documented in several studies. VR has evolved from experimental technology to a widely used tool in industry. The main point out that VR allows simulating work environments without interrupting production, thus increasing efficiency and safety [7].

Fig. 2. A simple demonstration of collaborative design testing in VR [10]

Kaizen, as a philosophy of continuous improvement, finds strong support in digital technologies. This digital technology is like digital tools, which include VR too, that accelerate problem identification, increase engagement, and foster innovative solutions [8,9].

The article "The effect of virtual reality-enabled manufacturing practices on production efficiency practical applications of VR in companies between 2010 and 2020. According to them, VR helps to visualize complex processes, reveal bottlenecks and suggest improvements. The article "Use of Virtual Reality to Improve Learning Experience on a Lean Manufacturing Course" confirms the benefits of VR in the field of lean manufacturing, where VR allows for testing designs before they are put into practice [10,11].

The literature shows that VR strongly supports the implementation of Kaizen workshops. It facilitates better problem identification, simulation of processes without interrupting production, and increases participant engagement. Thus, companies can innovate, optimize and improve their processes more efficiently in the spirit of lean manufacturing principles thanks to VR [12].

3. POSSIBILITIES OF APPLYING FOR THE VIRTUAL REALITY FOR KAIZEN WORKSHOP

This chapter compares the traditional approach with the use of virtual reality (VR) as a support tool during the different phases of a Kaizen workshop.

- **Defining the goal of the workshop**

Traditionally, goals, such as reducing waste or increasing efficiency, are set based on discussions. However, VR allows the actual state of processes to be visualised (e.g., by animating a line or warehouse), allowing participants to better understand the problem and formulate realistic goals. VR also increases their engagement by allowing them to 'experience' the current state.

- **Data collection and analysis of the current state**

Routinely, existing data is analysed, and bottlenecks are identified. VR offers detailed visualisation of processes in real time - participants can virtually move through the workplace, perceive inefficiencies, and better understand current challenges.

- **Generate ideas for improvement**

Instead of exclusively using brainstorming or 5 Whys, VR allows for immediate testing of suggestions (e.g. new station layouts) and tracking their impact in a simulated environment.

- **Planning the implementation of changes**

While planning tools such as Gantt charts are classically used, VR can visually represent the future state of processes after changes have been applied, which supports better decision-making.

- **Implementation and staff training**

VR enables hands-on training without the risk of affecting real production. Employees can try out new procedures or operate equipment in a virtual environment, which increases their confidence and reduces errors.

- **Monitoring and evaluation of results**

Instead of tracking metrics only on paper, VR enables their visualization in real time. Efficiency, time loss or quality can be directly analyzed during the simulation, which speeds up feedback.

- **Sharing results and standardization**

Results are usually presented through presentations. However, VR can also illustrate them to other teams, serve as training material and ensure knowledge transfer.

As can thus be seen, VR strongly promotes efficiency, commitment and a culture of continuous improvement. Its integration into Kaizen workshops represents a modern and innovative approach to process optimization.

4. RESULTS AND DISCUSSION

The implementation of virtual reality (VR) as a tool in Kaizen workshops brings several implications, from efficiency gains to technological challenges. This chapter discusses both the positive and negative aspects of using VR in this context.

1.1 Positive consequences

- **Improving processes more efficiently**

VR enables realistic visualization of production and logistics processes, making it easier to identify bottlenecks, inefficiencies and waste. With simulations, participants can safely test different designs and quickly identify the most appropriate solution.

- **Increased engagement and development of practical skills**

Interactive VR environments increase participant engagement. They can actively test proposed changes, which improve their understanding of Kaizen principles while developing their practical skills.

- **Saving time and costs**

VR eliminates the need for physical interventions during the workshop, saving costs and time. Simulations allow multiple variations to be tested without interrupting production or requiring additional investment in materials.

1.2 Negative impacts and challenges

- **Technological complexity and implementation costs**

Incorporating VR requires investment in hardware, software and training. For smaller organizations, this barrier can be significant, especially if in-house expertise is lacking.

- **Limits of virtual simulation**

Not all real-world conditions, such as vibration, temperature or noise, can be accurately simulated. This can affect the credibility of some conclusions from the workshop.

- **Reduction of personal interaction**

Kaizen workshops are built on teamwork and direct communication. Over-reliance on VR can weaken group dynamics and limit the informal exchange of ideas.

1.3 Impact on organisational culture

The introduction of VR can strengthen the perception of innovation in the enterprise and motivate employees to actively engage in improvement. At the same time, however, it can create resistance to change and concerns about technical skills shortages. It is therefore important to ensure sensitive implementation and consistent training.

Virtual reality brings a modern dimension to Kaizen workshops, promoting efficiency, engagement, and cost savings. But its successful deployment depends on the organisation's readiness to manage technological, organisational, and cultural challenges. That is why VR is currently recommended as a complement to physical workshops rather than as a complete replacement for them.

5. CONCLUSION

Virtual reality (VR) is proving to be an extremely useful tool in implementing continuous improvement philosophies such as Kaizen. Integrating VR into Kaizen workshops enables realistic visualization of processes, identification of bottlenecks and testing of innovations without disrupting real production. This modern approach also promotes effective training, increases participant engagement and enables faster and more accurate decision making [13,14].

Despite the many benefits, it is also important to consider the challenges associated with the use of VR, such as initial investment and technical limitations. As technology evolves, these can be expected to be gradually overcome, making VR even more accessible and effective. For organizations looking to keep up with modern trends and improve their processes, the combination of VR and Kaizen presents a unique opportunity to achieve greater productivity and competitive advantage in today's dynamic industry environment.

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0633/24.
This work was supported by the KEGA Agency under the contract no. 001ŽU-4/2024.
This work was supported by the KEGA Agency under the contract no. 011ŽU-4/2025.

References

[1] HARAUSOVÁ, H., 2012. Procesné prístupy v manažérstve kvality. Prešov: Prešovská univerzita v Prešove. 98 s. ISBN 978-80-555-0546-6

[2] ANTONY, J., SNEE, R., HOERL, R. (2017). Lean Six Sigma: yesterday, today and tomorrow. EMERALD GROUP PUBLISHING LIMITED, Vol. 34, Issue 7, pp. 1073 – 1093. https://doi.org/10.1108/IJQRM-03-2016-0035

[3] MIČIETA, B., KRÁL, J., 1998. Plánovanie a riadenie výroby. Žilina: Žilinská univerzita v Žiline. 210 s. ISBN 80-7100-430-8

[4] FRANKEN, J., VAN DUN, D., WILDEROM, C. (2024). Kaizen Event process factors for operational performance improvement: an archival study. Production Planning & Control, pp. 1–15. https://doi.org/10.1080/09537287.2024.2358402

[5] IŽOL, P., DEMKO, M., VRABEĽ, M., BRINDZA, J. (2022). Trendy vývoja CNC obrábania a CAM systémov. Transfer inovácií, Vol. 46, pp. 4-9

[6] ZYWICKI, K., ZAWADZKI, P., BUN, P., GORSKI, F. (2020). Employee Training in an Intelligent Factory Using Virtual Reality. IEEE Access, Vol. 8, pp. 135110-135117. https://doi.org/10.1109/ACCESS.2020.3010439

[7] PAÍNO AMBROSIO, A., & RODRÍGUEZ FIDALGO, M. I. (2020). Past, present and future of Virtual Reality: Analysis of its technological variables and definitions. Culture &Amp; History Digital Journal, Vol. 9(1), pp. e010. https://doi.org/10.3989/chdj.2020.010

[8] AL-ANSI, M., JABOOB, M., GARAD, A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. Social Sciences & Humanities Open, Vol. 8, pp. 3-4. https://doi.org/10.1016/j.ssaho.2023.100532

[9] KRAJČOVIČ, M., 2020. Digitálne projektovanmie výrobných a logistických systémov. Žilina: Žilinská univerzita v Žiline. 82 s. ISBN 978-8055417479

[10] SAYEG, G., AMADO-MORANCHEL, N., ACERO, A. (2024). Use of Virtual Reality to Improve Learning Experience on a Lean Manufacturing Course. 2024 ASEE Annual Conference & Exposition, pp.13. https://doi.org/10.18260/1-2--4822

[11] XIONG, Y., LAM, H., KARIMI, S. (2024). The effect of virtual reality-enabled manufacturing practices on production efficiency. International Journal of Production Economics. Vol. 274, Art. 109288. https://doi.org/10.1016/j.ijpe.2024.109288

[12] FRANKEN, J., VAN DUN, D., WILDEROM, C. (2021). Kaizen Event Process Quality: Towards a Phase-based Understanding of High-Quality Group Problem Solving. International Journal of Operations & Production Management. Vol. 41, pp. 962-990. https://doi.org/10.1108/IJOPM-09-2020-0666

[13] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research

[14] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

Martin BUZALKA [1], Peter BUBENIK[2], Ľuboslav DULINA[3]

APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN TRANSPORT AND LOGISTICS PROCESSES

Abstract

In today's rapidly evolving technological era, many modern solutions are replaced before being fully implemented. Logistics is a sector where optimization and automation are key. This paper presents specific applications of artificial intelligence in warehouse management, transport planning, and autonomous delivery systems. Autonomous mobile robots (AMRs) represent a major innovation, offering flexibility and human collaboration capabilities. AI also plays a crucial role in dynamic route planning and cost reduction. The article concludes with the challenges of integrating AI into traditional logistics processes.

Key words: artificial intelligence, logistics, distribution processes, AMR,

1 INTRODUCTION

Artificial intelligence is significantly transforming logistics and transportation. Technologies such as machine learning and AI help streamline operations, solve complex transport challenges, and support more accurate data-driven decision-making. Transport companies, airlines, and logistics providers are using AI to automate warehouses, optimize routes, predict demand, and test autonomous delivery vehicles. The greatest benefits of AI can be seen in areas such as smart transport planning, autonomous vehicles, and robotic warehouses. Machine learning algorithms process vast amounts of data — including historical demand trends, real-time traffic conditions, weather forecasts, and local events — to enable more efficient transport planning and overall logistics optimization. AI also simplifies the management of various dynamic factors, such as driver availability, traffic conditions, fuel prices, warehouse capacity, and legal requirements. Intelligent optimization algorithms can automatically plan the most efficient routes, allocate drivers and vehicles more effectively, coordinate loading operations, and maximize vehicle utilization [1].

[1] Martin Buzalka, Ing., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia; martin.buzalka@fstroj.uniza.sk

[2] Peter Bubeník, Doc., University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovakia; peter.bubenik@fstroj.uniza.sk;

[3] Ľuboslav Dulina, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, luboslav.dulina@fstroj.uniza.sk

This article explores current and emerging applications of AI in transport and logistics. It examines how modern technologies help increase the efficiency, safety, and reliability of logistics processes — from autonomous vehicles and automated warehouses to intelligent transport planning systems.

2 USE OF AUTONOMOUS MOBILE ROBOTS (AMR)

Autonomous Mobile Robots (AMRs) are a type of robot capable of independently perceiving and navigating their environment. Utilizing advanced sensors, artificial intelligence (including machine learning), and onboard computing, AMRs can plan routes and operate without physical guidance systems. Thanks to cameras and sensors, AMRs can dynamically respond to unexpected obstacles—such as a fallen box or a group of people—by slowing down, stopping, or rerouting to continue their tasks. They represent an evolution of Automated Guided Vehicles (AGVs), which rely on fixed paths defined by floor markers or RFID infrastructure, limiting their flexibility. In modern, fast-paced warehouses and automated production halls, fixed-path systems are increasingly seen as inefficient. Many companies are therefore replacing AGVs with AMRs, which can adapt their routes in real time. As of 2025, deploying AGVs instead of AMRs is considered questionable, with a clear trend toward full AMR adoption in the near future [2,3].

2.1 Use of AMRs in Warehouses

The Japanese online retailer Rakuten has developed the world's most automated distribution warehouse, using AI-powered Autonomous Mobile Robots (AMRs) for order fulfillment. Hundreds of AMRs operate within a grid-based storage system(fig 1.), autonomously locating and delivering racks with requested items. Workers (pickers) stationed around the warehouse receive notifications when a robot brings them the required shelf. The entire system is controlled by an automated management software. The warehouse uses a goods-to-person approach, eliminating the need for workers to walk around searching for products. Each item is sent to the nearest available picker, ensuring efficient workload distribution.Thanks to advanced AI technologies, the warehouse processes up to 1.1 million orders daily, offering same-day or next-day delivery, with two-hour delivery windows.

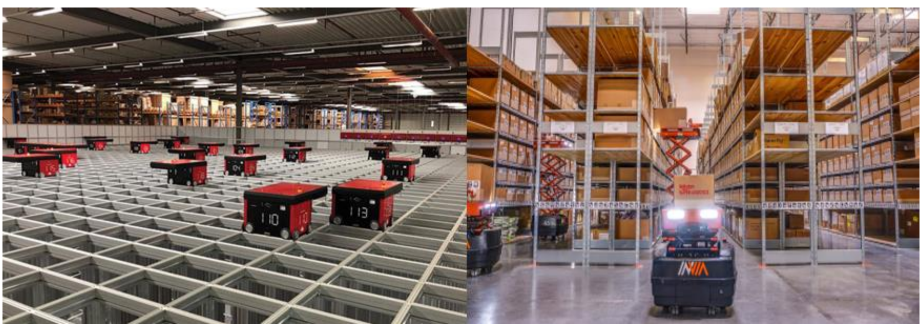


Fig. 1. Use of AMRs in Rakuten's Automated Warehouse [4]

This system requires only one-sixth of the workforce compared to traditional warehouses, optimizing coordination between robots and humans for faster and more flexible logistics [4, 5].

2.2 Use of AMRs Outside Warehouses

Fig. 2 Uber Eats Delivery Robot in Japan [6]

Autonomous Mobile Robots (AMRs) are no longer limited to warehouses and industrial facilities. Advances in technology and AI have enabled their deployment in outdoor environments, especially in last-mile delivery. One of the fastest-growing applications is autonomous food delivery, which gained momentum during the COVID-19 pandemic as companies sought to minimize physical contact. Pioneers such as Starship Technologies, Uber Eats, Just Eat, and DoorDash began testing robotic delivery services around 2020. Starship Technologies, founded in Estonia in 2014, was among the first to experiment with autonomous deliveries(Fig 2.), but the pandemic accelerated large-scale implementation worldwide.Today, AMRs operate on sidewalks and bike lanes in urban areas, delivering food and parcels without the need for human couriers. This technology is already in use in the U.S., U.K., Estonia, Finland, and beyond. Its key benefits include low operating costs, 24/7 availability, and efficient navigation in dense urban traffic. With continued technological improvements, autonomous delivery systems are expected to expand and evolve further in the coming years [6].

3 TRANSPORT OPTIMIZATION AND ROUTE PLANNING

Efficient route planning and traffic management are essential in logistics. One of the key challenges is the Vehicle Routing Problem (VRP), where companies must assign vehicles to destinations in a way that minimizes delivery time and cost. For businesses handling thousands of deliveries daily, manual planning is nearly impossible. Traditional algorithms struggle due to the complexity of variables like traffic conditions, delivery windows, vehicle capacity, driver availability, and route changes. Artificial intelligence (AI) plays a major role in addressing this. Advanced planning systems use AI to analyze multiple routing factors in real time and determine optimal routes. Reinforcement Learning (RL) allows algorithms to learn effective routing strategies through trial and error. AI continuously improves routing decisions by learning from past outcomes — reducing delivery times, cutting costs, and boosting efficiency. For logistics providers, RL is a powerful tool for dynamic route optimization in ever-changing transport environments [7, 8].

3.1 Examples of AI Applications in Transport Routing

International transport companies offer practical examples of how artificial intelligence (AI) can be used to optimize vehicle routing. UPS uses reinforcement learning to adapt routes to individual drivers, aiming to minimize left-hand turns in heavy traffic, thereby reducing delivery times and improving accuracy. The company's "ORION" software analyzes road speed patterns and generates strategic daily route plans, helping optimize courier movements. With 10,000 routes optimized through ORION, UPS saves up to 5.7 million liters of fuel annually. Reducing driving distance by just 1.6 km per driver per day has resulted in annual savings of up to $50 million. FedEx combines navigation systems, vehicle speed data, and historical traffic information to create smooth and reliable courier routes. This system helps avoid unexpected congestion and delays, ensuring fast and efficient deliveries. According to FedEx, AI-enhanced routing helped reduce delivery distances by 10.6 million kilometers in a single year. Convoy developed a tool called "Drop & Swap," which uses AI to automate trip planning for truck drivers carrying partially loaded trailers. Through a mobile app, drivers can easily coordinate cargo exchanges along the route, enabling faster transitions to the next load without unnecessary downtime. This system increases transport efficiency and minimizes the time trucks spend driving empty or waiting for new cargo [9, 10].

4 USE OF AUTONOMOUS VEHICLES

Autonomous vehicles are gradually transitioning from an innovative concept to everyday reality. Transport companies are actively developing autonomous trucks, ships, drones, and other vehicles with the potential to revolutionize the way goods are transported. Companies such as Tesla, Embark, TuSimple, and Aurora are experimenting with advanced technologies that enable long-distance freight delivery without driver intervention (Fig. 3).

Fig. 3 Autonomous Vehicle by TuSimple [13]

Organizations like the Autonomous Vehicle Computing Consortium are also contributing to the development of this technology by working on standards that allow products from different manufacturers to operate together within intelligent transport networks [2, 11].

5 CHALLENGES ASSOCIATED WITH THE IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) holds significant potential for improving transportation, but its implementation faces several challenges—not only technical, but also cultural and organizational—which often slow down broader adoption. Many companies struggle with integrating AI into daily operations. According to Zeydan [14], the main barriers include:

- Resistance to change – Many organizations rely on long-standing processes. Switching to AI requires major workflow changes, which can lead to uncertainty and mistrust among employees.
- Weak data infrastructure – Effective AI needs high-quality data, but many transport firms still use paper documentation or outdated IT systems, limiting AI's impact.
- Shortage of skilled experts – AI integration requires specialists such as data scientists and engineers. Their scarcity delays innovation and complicates implementation.

Despite these obstacles, companies can take practical steps to maximize AI's value [14]:

- Transforming corporate culture – Key to AI adoption is employee education and collaboration between logistics and IT teams. Training and workshops help build understanding and acceptance of AI.
- Improving data infrastructure – Companies must invest in modern IT, sensors, and control systems to support accurate data collection and analysis for AI.
- Innovating business models – AI's full potential emerges when combined with new strategies, such as logistics automation, predictive routing, and smart fleet management—driving efficiency and competitiveness.

6 CONCLUSION

Artificial intelligence is reshaping the logistics sector through innovations such as warehouse robotics, autonomous vehicles, real-time tracking, and predictive planning. Companies that adopt AI early gain a competitive edge, while late adopters risk losing market share. Successful implementation requires more than just technology—it demands cultural change, employee training, and integration with existing systems. [15]

A key challenge is the lack of readiness among the workforce and outdated infrastructure. To overcome this, firms must invest in modern IT, high-quality data sources, and clear internal communication. [16] Pilot projects and focused deployment in areas without existing solutions can ease the transition and build in-house AI expertise.

The future of logistics lies in the synergy between advanced AI technologies and the operational experience of logistics companies. Strategic integration with TMS, WMS, ERP, and IoT will drive greater efficiency, productivity, and customer satisfaction.

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0633/24.
This work was supported by the KEGA Agency under the contract no. 011ŽU-4/2025.

References

[1] BROOKS, R. A. (2024). *AFP.*

[2] DIXIT, P. N. (2023). Intelligent warehouse automation using robotic system. *Lecture Notes in Electrical Engineering*, pp. 435–443. doi: https://doi.org/10.1007/978-981-19-6581-4_34.

[3] ELIJAH, O. R. (2018). An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet of Things Journal*, 5(5), pp. 3758–3773.

[4] GUO, Y. (2025). Successful Stories on the Usage of Technologies in Service Industries. *Technological Innovations in the Food Service Industry*, p. 34. doi: 10.4018/979-8-3693-7683-6.ch010.

[5] HUGHES, D. L. (2019). Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda. *International Journal of Information.*

[6] IVANOV, D. D. (2018). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, pp. 829–846.

[7] KLUMPP, M. (2017). Automation and artificial intelligence in business logistics systems: human reactions and collaboration requirements. *International Journal of Logistics: Research and Applications*, 21(3), pp. 224–242. doi: https://doi.org/10.1080/13675567.2017.1.

[8] KOLODNY, L. (2021). TuSimple says its self-driving trucks shaved 10 hours off a 24-hour run. *Available on the internet:* https://www.cnbc.com/2021/05/19/tusimple-self-driving-trucks-saved-10-hours-on-24-hour-run.html.

[9] LI, R. Z. (2017). Intelligent 5G: When cellular networks meet Artificial Intelligence. *IEEE Wireless Communications*, 24(5), pp. 175–183. doi: https://doi.org/10.1109/mwc.2017.1600304wc.

[10] LOGISTIC, R. S. (2018). *Available on the internet:* https://www.prnewswire.com/news-releases/rakuten-super-logistics-expands-national-presence-into-chicagoland--new-jersey-markets-300706687.html.

[11] MANSOURSAMAEI, M. M.-R.-R. (2023). Machine learning for promoting environmental sustainability in ports. *Journal of Advanced Transportation*, pp. 1–17. doi: https://doi.org/10.1155/2023/2144733.

[12] MÜLLER, V. C. (2016). Future progress in Artificial Intelligence: A survey of expert opinion. *Synthese Library.*

[13] SOLANKI, A. (2024). AI Applications for Improving Transportation and Logistics Operations. *International Journal of Intelligent Systems and Applications in Engineering*, 12.

[14] ZEYDAN, E., & B. (2022). Recent advances in data engineering for networking. *IEEE Access*, pp. 34449–34496.

[15] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research

[16] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

Matúš CAGALA[1], Peter SZABÓ[2]

THE IMPACT OF ENVIRONMENTAL ASPECTS ON CONSUMER DECISION-MAKING ACROSS GENERATIONS

Abstract

The rising attention to sustainability and environmental protection is fundamentally changing consumer behaviour. Consumers are increasingly considering environmental attributes in their purchasing decisions, creating a need for a deeper understanding of generational differences in perceptions of these aspects. The aim of this paper is to analyse how environmental attributes influence consumer decision-making across generations Baby Boomers, X, Y and Z, and to identify which of these attributes are most important to each generation.

Key words: generations, consumers, green products

1. INTRODUCTION AND LITERATURE REVIEW

Currently, the increasing interest in sustainable development and environmental protection is one of the most significant trends influencing consumer behaviour. Growing environmental awareness leads to consumers more often taking environmental attributes into account when choosing products, which in turn influences companies' marketing strategies and requires adaptation to new market demands. This creates a pressing need for a deeper understanding of how different generations perceive environmental aspects and how these aspects influence their decision-making processes. The term „generation" refers to a group of people born in the same period who have shared common cultural, historical and social experiences that form their values, attitudes and purchasing behaviour. There are several generations, which include Baby Boomers, Generation X, Generation Y and Generation Z [1].

- **Baby Boomers** (1946-1960) are the generation that experienced the post-war economic boom, demonstrating brand loyalty, more traditional values and an importance on product quality [4].

[1] Matúš CAGALA, Ing. Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Ulica Jána Bottu 2781/25, 917 24 Trnava, Slovakia, matus.cagala@stuba.sk
[2] Peter Szabó, Ing. PhD. Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology, Slovak University of Technology in Bratislava, Ulica Jána Bottu 2781/25, 917 24 Trnava, Slovakia, dagmar.babcanova@stuba.sk

- **Generation X** (1961-1980) is described as a pragmatic and independent generation. These consumers often require detailed product information [7].
- **Generation Y** (1981-1995) grew up in a period of rapid technological transformation. They are characterized as technologically skilled, socially responsible [4].
- **Generation Z** (1996-2010) is characterized by high digital competence, an inclination towards innovation, and a strong emphasis on brand authenticity and transparency [1].

Modern marketing increasingly reflects the growing consumer attention to the environmental responsibility of companies and their products [2]. In the context of brand management, environmental attributes are an increasingly important factor in brand differentiation and identification. Industrial companies that clearly and trustworthily communicate the environmental aspects of their products and activities can achieve greater customer loyalty and strengthen their competitive position [3]. Several studies have addressed how environmental aspects influence consumer decision making. Research in the field of green marketing emphasizes the growing influence of green certifications, sustainable packaging and environmentally friendly production processes on purchasing decisions [5]. Triwijayati conducted empirical research on a sample of 1000 consumers and confirmed that green aspects have a significant role in consumer decision making [8]. Similarly, Lazovic's research confirmed the importance of green aspects in forming positive brand perceptions and consumer trust [2]. Studies in the digital environment (e.g., Abu-Dalbouh) demonstrate that social media and online reviews play a key role in the dissemination of information about green products [9]. Although there is a many of research addressing green consumer behaviour and preferences, most of it has been without explicitly identifying generational segments within a single integrated framework [10]. Existing literature indicates that eco-preferences can vary considerably not only by age, but also by socio-economic context and regional specificities [6]. The present paper fills research gap by comprehensively analysing the perception of eco-attributes across Baby Boomers, X, Y, and Z generations.

2. METHODS AND METHODOLOGY

The research was conducted through a questionnaire survey. The questionnaire was distributed in both printed and electronic formats. The electronic version of the questionnaire was distributed through the Vyplnto.cz platform, while the printed version was distributed through personal contacts, including family members and acquaintances. Data collection was conducted between 1 December 2024 and 9 February 2025. The research sample consisted of respondents from four generational cohorts: Baby Boomers, Generation X, Generation Y and Generation Z. A total of 422 respondents were contacted and 331 questionnaires were completed correctly. This represents a questionnaire return rate of 78.50%. In terms of economic background, respondents were mainly employed persons, students and retired persons. However, the unemployed, entrepreneurs, temporary workers and persons on parental leave were also represented. The questionnaire contained 17 questions, two of which were selected for analysis in this paper. Both questions were semi-open questions. Respondents could select multiple response options, while at the same time having the opportunity to add their own opinion. The maximum number of responses was limited to three, in order to capture a wider range of respondents' preferences. A chi-square test of independence in Microsoft Excel was used to process and analyse the data, supported by a graphical representation of the results. Two main research questions were formulated as part of the research:

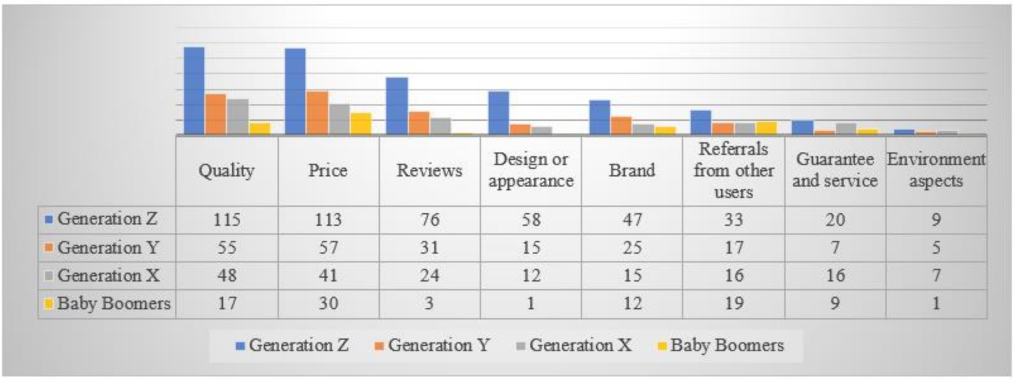
- Which factors most influence the consumer decision-making of each generation?
- What specific environmental aspects are priorities for each generation?

These questions serve as a basis for comparison between generational groups and to identify the level of importance of environmental aspects in their purchasing behaviour.

3. RESULTS AND DISCUSSION

RQ 1: *Which factors most influence the consumer decision-making of each generation?*

Figure 1 illustrates the factors that influence consumer purchasing decisions across four generations: Generation Z, Generation Y, Generation X and Baby Boomers. Each bar represents the number of times a particular factor was selected within that generation.



	Quality	Price	Reviews	Design or appearance	Brand	Referrals from other users	Guarantee and service	Environment aspects
Generation Z	115	113	76	58	47	33	20	9
Generation Y	55	57	31	15	25	17	7	5
Generation X	48	41	24	12	15	16	16	7
Baby Boomers	17	30	3	1	12	19	9	1

Fig. 1. Purchasing decision factors (own processing)

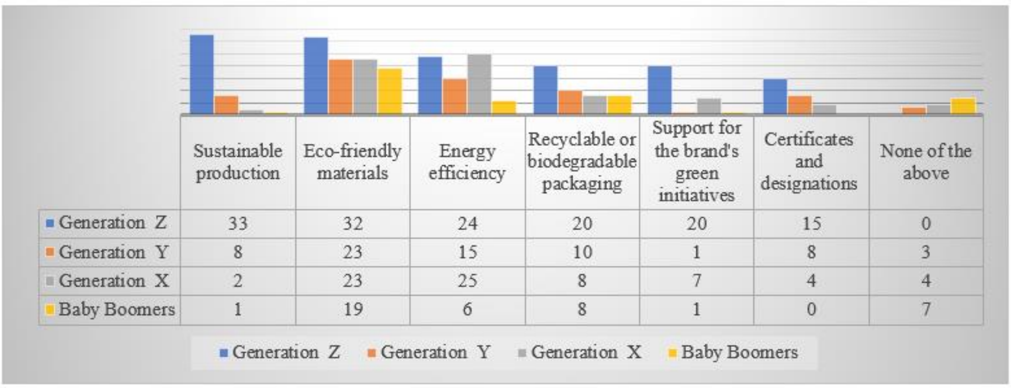
Chi-square test results:

- Chi-square value: 59.30
- p-value: 0.0000163
- Degrees of free (df): 21

Because the p-value is significantly less than the set significance level (α = 0.05), it means that there is a statistically significant difference between generations in how they choose products according to various factors (design, quality, price, etc.). Generation Z (the youngest) assigns the greatest importance to the factors of quality (115) and price (113). They are also interested in reviews (76), product design or appearance (58), and brand (47). They are also sensitive to recommendations from other users (33) and are also interested in warranty and service (20). Environmental aspects (9), although lower in priority, rank higher than Baby Boomers. Generation Y is also strongly oriented towards quality (55) and price (57). Reviews (31), brand (25) and design (15) play an important role. Recommendations from others (17) and guarantee (7) are less important. Environmental aspects (5) are the least important of all the factors considered. For Generation X, quality (48) is most important, followed by price (41) and reviews (24). Compared to younger generations, they attach less importance to design (12), brand (15) or recommendations from other users (16). Interestingly, guarantee and service (16) are more important to them than to Generations Y and Z.This oldest generation places the least importance of all generations on most factors. They value price (30) and quality (17) the most. Reviews (3), design (1), brand (12) and recommendations (10) play a minimal role for them. Guarantee and service (9) are relatively important to them. Environmental aspects (1) are almost negligible.

RQ2: *What specific environmental aspects are priorities for each generation?*

Figure 2 shows the importance of specific environmental aspects in purchasing decisions by generation (Z, Y, X and Baby Boomers). These include aspects such as sustainable production, eco-friendly materials, energy efficiency, etc.



	Sustainable production	Eco-friendly materials	Energy efficiency	Recyclable or biodegradable packaging	Support for the brand's green initiatives	Certificates and designations	None of the above
Generation Z	33	32	24	20	20	15	0
Generation Y	8	23	15	10	1	8	3
Generation X	2	23	25	8	7	4	4
Baby Boomers	1	19	6	8	1	0	7

Fig. 2. Environmental aspects (own processing)

Chi-square test results:

- Chi-square value: 73.55
- p-value: 0.00000112
- Degrees of free (df): 18

Because the p-value is below the 0.05 level of significance it means that there is a statistically significant difference between generations in their preferences of environmental aspects in their purchasing decisions.

Generation Z most frequently indicated sustainable production (33), environmentally friendly materials (32), energy efficiency (24), recyclable or biodegradable packaging (20), support for green brand initiatives (10), and certificates and labels (15) as important factors. Option „none of the above“ factors were chosen by any respondent from this generation. For Generation Y, eco-friendly materials were the most frequently chosen (23), followed by energy efficiency (15), recyclable or biodegradable packaging (10), certificates and labels (8), sustainable production (8), and support for green brand initiatives (1). The option „none of the above“ was selected by 3 respondents. Generation X most frequently indicated energy efficiency (25) and eco-friendly materials (23), followed by recyclable packaging (8), support for green brand initiatives (7), certificates and labels (4), and sustainable production (2). The option „none of the above“ was selected by 7 respondents. Baby Boomers most frequently mentioned eco-friendly materials (19), followed by energy efficiency (6), recyclable or biodegradable packaging (6), support for green brand initiatives (4), sustainable manufacturing (1), and certificates and labels (0). Seven respondents from this group did not choose any of the above mentioned environmental factors.

The analysis showed generational differences in purchasing decisions. Generation Z emphasises quality, price, reviews and design, being the most sensitive to environmental aspects. Generation Y shows similar preferences, but environmental aspects are less important. Generation X and Baby Boomers prefer traditional aspects such as price, quality and guarantee; ecology plays a marginal role. In the environmental area, Generation Z prefers green production, recyclable packaging and certificates. Generation Y values eco-friendly materials and economy, Generation X practical benefits such as energy efficiency. Baby Boomers are not interested in environmental issues.

From a brand management perspective, it is recommended that industrial companies emphasize eco-friendliness - e.g. certificates, packaging, materials - when they interact with Generation Z and Generation Y. Functional benefits should be emphasised with Generation X and traditional values - quality, price, reliability - with Baby Boomers. The research relies on questionnaires, which presents limitations such as socially desirable responses and a limited sample. In the future, qualitative research and tracking of real behaviour in the B2B segment is recommended.

4. CONCLUSION

The present paper supports that environmental aspects of products play a role in consumer decision-making across generational cohorts, but the level of influence varies between generations. Generations Y and Z have shown the highest sensitivity to environmental attributes, with quality and price remaining the dominant factors for all generations. Chi-square test results showed statistically significant differences between generations in the evaluation of purchasing factors as well as in preferences for specific environmental product attributes (e.g. eco-packaging, certifications and transparency of production). Recommendations for industrial companies:

Take generational differences into account

Different generations have different values, purchasing preferences and perceptions of green products. Generations Z and Y expect sustainability from brands, Generation X and Baby Boomers prefer proven quality, functionality and long-term value.

Invest in eco-innovation

Focus on sustainable materials, energy efficient technologies and recyclable packaging. Create products with a lower environmental burden that can be certified (e.g. ISO 14001, EPD, FSC). Use eco-design principles already in the product development phase (eco-design).

Increase transparency and credibility of environmental claims
Provide clear and verifiable data on the environmental performance of products (e.g. carbon footprint, life cycle). Avoid greenwashing - misleading environmental communication without a real basis.

Strengthen digital communication
Implement interactive online tools (e.g. emission savings calculators, 3D product presentations). Use social media, and professional platforms to spread eco-innovation and build trust with customers and partners.

Build an eco-oriented brand and company culture
Make sustainability a core value of the company. Educate employees on the importance of environmental responsibility. Participate in projects focused on circular economy and eco-innovation in the sector.

References

[1] CAGALA, M., BABČANOVÁ, D.: Preferences of Generations of Customers in Slovakia in the Field of Marketing Communication and Their Impact on Consumer Behaviour. Administrative Sciences, vol. 14, 2024, article no. 224. Dostupné online: https://doi.org/10.3390/admsci14090224

[2] LAZOVIĆ, I.: Ecological Marketing in the Function of Sustainable Development. *Knowledge – International Journal*, vol. 47, no. 1, 2021, pp. 153–157. Available on the internet: https://www.ceeol.com/search/article-detail?id=1075670

[3] NAYAK, M., MEGHA, K. P.: Analysis of Consumer Decision-Making in the Influencer Market. *International Research Journal on Advanced Science Hub*, vol. 6, no. 09, 2024, pp. 263–270. Available on the internet: https://doi.org/10.47392/IRJASH.2024.037

[4] SMOLKA, S.: Charakteristika generácií slovenských spotrebiteľov. *Marketing Science & Inspirations*, vol. 14, no. 1, 2019, pp. 2–11. ISSN 1338-7944. Available on the internet: https://msijournal.com/charakteristika-generacii-slovenskych-spotrebitelov/

[5] CHEN, Y., SUN, Z., WU, Q.: Research on Eco-Product Supply Chain Decision-Making and Coordination Under Different Subsidy Strategies with Ecological Cost-Sharing Contracts. *Applied Sciences*, vol. 15, no. 5, 2025, article no. 2462. Available on the internet: https://doi.org/10.3390/app15052462

[6] ŠOSTAR, M., RISTANOVIĆ, V.: Assessment of Influencing Factors on Consumer Behavior Using the AHP Model. *Sustainability*, vol. 15, no. 13, 2023, article no. 10341. Available on the internet: https://doi.org/10.3390/su151310341

[7] ISMAIL, A., DORA, Y. M., HIDAJAT, T.: Consumer Decision Making Model Process but as Independent Factors: And Its Influence on Purchasing Behavior. *Preprints*, February 2024. Available on the internet: https://doi.org/10.20944/preprints202402.1188.v1

[8] TRIWIJAYATI, A.: Decision Making Style, Generation, and Social Stratification: An Explorative Study of Indonesia Consumer. *Asean International Journal of Business*, vol. 4, no. 1, 2025, pp. 47–62. Available on the internet: https://doi.org/10.54099/aijb.v4i1.1184

[9] ABU-DALBOUH, H. M., FREIHAT, M. M., JAWARNEH, R. I., SALIM, M. A. M., ALATEYAH, S. A.: Analyzing Consumer Decision-Making in Digital Environments Using Random Forest Algorithm and Statistical Methods. *International Journal of Advanced Computer Science and Applications*, vol. 16, no. 3, 2025, pp. 1186–1194. Available on the internet: https://www.researchgate.net/publication/390455980

[10] DEWI, N., HERLON, M., PEBRIAN, S., KUSUMAWATY, Y.: Consumer Perception of Palm Sugar Products in Rokan Hulu District, Indonesia: A Prospective Analysis Approach. *4th International Conferences in Social Sciences (ICONISS): Urban Innovation*, 2024, pp. 144–155 Available on the internet: https://doi.org/10.18502/kss.v9i26.17080

Lukáš JURÁČEK[1], Lukáš JURÍK[2], Helena MAKYŠOVÁ[3]

OVERVIEW OF SELECTED METHODOLOGIES AND TOOLS FOR ASSESSING THE LEVEL OF GREEN PRODUCTION

Abstract

The aim of this paper is to analyse selected methodologies and tools for the evaluation of green or organic production based on 13 scientific articles. The identified approaches include LCA, fuzzy methods, TOPSIS, ANP, DEMATEL and certifications such as ISO 14001 or EMAS. The indicators assessed focus on energy, emissions and waste. The paper highlights the benefits, limitations of the methodologies and the need to align them with global frameworks. The findings can serve as a basis for further research.

Key words: green manufacturing, environmental assessment, sustainability, manufacturing companies

1 INTRODUCTION

The assessment of the level of application of green production includes various methodologies that integrate environmental aspects into production processes. The aim of these methodologies is to evaluate and increase the sustainability of production processes by reducing resource consumption, minimising waste and reducing emissions. The following sections outline some of the key methodologies used in the evaluation of green manufacturing derived from scientific publications:

- **Green Productivity Techniques - Green Productivity (GP)** is an approach that combines productivity improvements with sustainable environmental practices. It focuses on optimizing resource use, reducing emissions and minimizing waste while maintaining or improving economic performance. It uses tools such as the implementation of green technologies, energy-efficient equipment and renewable resources, while also emphasizing stakeholder involvement in environmentally responsible processes [1].

[1] Lukáš Juráček, Ing., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Ulica Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, lukas.juracek@stuba.sk
[2] Lukáš Jurík, Ing. PhD., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Ulica Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, lukas.jurik@stuba.sk
[3] Helena Makyšová, doc. Ing. PhD., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Ulica Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, helena.makysova@stuba.sk

- **TOPSIS methodology - The Technique for Ranking Preferences by Similarity to Ideal Solution (TOPSIS)** is a synthetic evaluation method used to rank green productions based on their environmental attributes. It allows the comparison of several alternatives according to criteria such as pollutant emissions, energy efficiency, renewable resource use and ecological footprint, thus providing a comprehensive environmental performance evaluation system [2].
- **Criteria systems and analytical models - Criteria systems for green manufacturing** are approaches that integrate environmental, economic and social considerations into business evaluation frameworks. They use decision-making and analytical models to identify and evaluate relevant green manufacturing indicators. Methods such as DEMATEL and the Analytic Network Process (ANP) allow for the creation of hierarchical decision structures and the visualization of relationships between criteria, thus supporting a comprehensive assessment of environmental performance [3].
- **Life Cycle Assessment (LCA) - LCA (Life Cycle Assessment)** is an analytical tool used to assess the environmental impacts of products, processes or services throughout their entire life cycle - from raw material sourcing, through production and distribution, to the disposal phase. It enables the identification of the main sources of environmental burdens and provides a comprehensive view of the environmental performance of the assessed system, which is the basis for designing improvements [4].
- **Fuzzy Comprehensive Assessment - Fuzzy logic** is an approach to environmental performance assessment that allows you to work with uncertainty and imprecision in decision making. It integrates multiple criteria into a hierarchical evaluation structure and combines both subjective and objective data. This approach allows for a comprehensive assessment of the environmental sustainability of products or processes in cases where traditional quantitative methods are not sufficient [5].
- **Environmental Assessment Tools -** Tools such as Green Performance Map (GPM), Environmental Value Stream Mapping (EVSM) and Waste Flow Mapping (WFM) are used to support environmentally oriented decision making in manufacturing. These tools are used to visualize environmental flows, identify inefficiencies, and determine areas with the greatest potential to improve a company's environmental performance [6].

Evaluating environmental performance requires selecting appropriate methodologies according to sector, objectives and available data, and combining them often provides a more holistic view. Certification schemes such as ISO 14001, EMAS or LEED also play an important role in enhancing credibility and promoting sustainable development:

- **ISO 14001:** is an internationally recognised standard for environmental management systems that provides a framework for the systematic management of the environmental aspects of an organisation. It aims to promote the reduction of negative environmental impacts through resource efficiency, waste minimisation and continuous improvement of environmental performance. The standard is part of the ISO 14000 family and is characterized by a structured approach that enables organizations to identify, monitor and control environmental risks in all phases of their operations [7].

- **EMAS (Eco-Management and Audit Scheme):** is a voluntary environmental management and audit scheme developed by the European Union to promote continuous improvement in the environmental performance of organisations. The scheme emphasises transparency, regular assessment of environmental impacts, public reporting and compliance with legislative requirements. With its rigorous standards and emphasis on data verifiability, EMAS can contribute to increasing an organisation's credibility and improving its market position [8].
- **LEED:** Leadership in Energy and Environmental Design (LEED) certification is a globally recognized symbol of success in sustainability in the building industry. It provides a framework for healthy, efficient and cost-effective green buildings. LEED certification is often applied in conjunction with other standards such as ISO 14001 to achieve higher standards of sustainability [9].
- **Other certifications:** Schemes such as BREEAM, Green Star and CASBEE also play an important role in the construction industry by setting benchmarks for sustainable building practices. These schemes assess various aspects of building performance, including energy efficiency, water consumption and indoor environmental quality, contributing to the overall sustainability of the built environment [10].

Certification schemes improve the environmental performance and competitiveness of businesses, but face challenges such as greenwashing, administrative complexity and cost [10, 11]. These shortcomings point to the need for greater transparency and standardisation across schemes [8].

2 METHODOLOGY

The aim of this paper is to analyze selected methodologies and tools to evaluate green or organic production based on scientific articles. From the Scopus, IEEE, Springer and MDPI databases, 13 scientific papers are selected that deal with the evaluation of environmental aspects of manufacturing in different sectors and regions. The selection criteria are the presence of a specific methodology (e.g. LCA, fuzzy logic, KPIs, certifications), practical application and focus on the manufacturing sector. Each paper will be analysed according to a single scheme:

- **Author -** The main authors of the articles listed by occurrence in the references.
- **Methodology/approach -** Method of evaluation used (e.g. LCA, TOPSIS).
- **Area of application -** Sector where the methodology has been applied.
- **Indicators assessed (KPI) -** Environmental indicators monitored (e.g. energy, emissions).
- **Benefits -** Main benefits of the methodology (e.g. simplicity, accuracy).
- **Disadvantages -** Limitations such as difficulty or unclear interpretation.
- **Certifications (C) -** Links to standards (ISO 14001, EMAS, SDGs).

3 RESULTS

In the table below, we provide an overview of 13 scientific papers that deal with the assessment of the level of green production. The table summarises the methodologies used, areas of application, indicators assessed and other key characteristics.

Table 1 Comparison of methodological approaches to environmental performance assessment in selected studies (Own research 2025)

Author	Name of methodology/ approach	Sector	KPI	Advantages	Disadvantages	C
[12]	GPM® Global Performance Model	different sectors	Sustainability in SME supply chains: energy, waste	link to the SDGs	implementation complexity	SDG, ESG
[13]	ISO 14001	manufac-turing	Policy impact on green tech: R&D investment, innovation	recognized standard	formality	ISO 14001
[14]	ANP /DEMATEL	electrical engineering	Green manufacturing impact on ESG success	good visualization of relationships	implementation complexity	none
[15]	Life Cycle Assessment (LCA)	automotive	LCA-enhanced KPIs in glass/ceramics: emissions, energy	environmental impact complexity	time requirements	ISO 14040
[16]	Green Productivity (GP)	Manufac-turing	KPIs in extrusion: energy, productivity, eco-efficiency	low cost, easy application	limited generalizability	ISO 14051
[17]	Fuzzy evaluation	textile industry	LCA: machining emissions, energy, waste	subjective factors included	Complex calculations	none
[18]	Hybrid model (LCA + fuzzy)	metal industry	CE KPIs: materials reused, recycled content, energy use	complexity and accuracy	higher complexity	ISO 14040 + fuzzy
[19]	ESG Indicators	automotive	ESG indicators: environment, social responsibility	comprehensive view of sustainability	low data accuracy	ESG, SDG
[20]	TOPSIS	Manufac-turing	KPI prioritization: product greenness, material efficiency	multi-criteria decision-making	requirement for precise data	ISO 14044
[21]	Waste Flow Mapping (WFM)	waste mana-gement	waste types, process inefficiencies	focus on waste flow	weak integration with the financial perspective	none

[22]	BREEAM	construction industry	ISO 50001, ISO 14001, LEED, BREEAM scores	flexibility	complex evaluation	BREE AM
[23]	EVSM, WFM, LCA	automotive	scrap, emissions, efficiency	waste identification	environmental aspects	ISO 14051
[5]	Fuzzy evaluation	green products	product green score	subjective factors included	calculations	fuzzy

The review shows that the most commonly used approaches include LCA, fuzzy evaluation and multiple decision methods. The indicators assessed most often related to energy consumption, emissions, material efficiency and performance against ESG criteria, with methodologies varying in terms of complexity, degree of objectivity and linkage to international standards.

4 CONCLUSION

The analysis of 13 papers confirmed the diversity of approaches to green manufacturing assessment, with LCA, fuzzy methods and MCDM approaches (e.g. TOPSIS, ANP) being the most commonly used. Indicators such as energy consumption, emissions, material efficiency and ESG were assessed. Many methodologies are linked to certifications (ISO, EMAS, BREEAM), which increases their credibility. The results underline the need to take into account sector specificities and support both the combination of methods and the standardization of indicators for better comparability.

Acknowledgement

This paper is a part of the project No. VEGA 1/0518/22 "*Implementation of integrated management systems with value-oriented requirements for the construction of modular collaborative workplaces*".
This paper was also created as part of the Young Researcher project No. 1347: " *Analýza uplatňovania metodík a nástrojov hodnotenia zelenej výroby v priemyselných podnikoch v SR* ".

References

[1] PRASETIA, B. (2024). Green Productivity Techniques for Analyzing Productivity in Agroindustry. *Tarjih Agribusiness Development Journal*, *4*(01), 24–30. https://doi.org/10.47030/tadj.v4i01.761

[2] JIA, X. (2009). Comprehensive Evaluation on Green Productions Based on TOPSIS Methodology. Information Management, Innovation Management and Industrial Engineering, 1, 570–572. https://doi.org/10.1109/ICIII.2009.143

[3] TSAI, S.-B., TSAI, S.-B., XUE, Y.-Z., HUANG, P.-Y., ZHOU, J., LI, G., GUO, W.-F., LAU, H., & SHANG, Z.-W. (2015). Establishing a criteria system for green production. 229(8), 1395–1406. https://doi.org/10.1177/0954405414535923

[4] PUJIANTO, T., BUNYAMIN, A., & WAFIYYAH, S. (2022). Pengukuran kinerja green manufacturing pada industri tahu sumedang untuk meningkatkan kinerja terhadap lingkungan menggunakan GSCOR dan LCA. Agrointek : Jurnal Teknologi Industri Pertanian, 16(2), 221–233. https://doi.org/10.21107/agrointek.v16i2.10831

[5] ZHANG, Q., & ZHANG, L. (2010). The evaluation and application of manufacturing green product based on fuzzy comprehensive assessment method. Fuzzy Systems and Knowledge Discovery, 3, 1085–1089. https://doi.org/10.1109/FSKD.2010.5569566
[6] SHAHBAZI, S., KURDVE, M., ZACKRISSON, M., JÖNSSON, C., & KRISTINSDORTTER, A. R. (2019). Comparison of Four Environmental Assessment Tools in Swedish Manufacturing: A Case Study. Sustainability, 11(7), 2173. https://doi.org/10.3390/SU11072173
[7] AMPOFO, A. (2018). Umweltzertifizierungen ISO 14001 und EMAS (pp. 171–187). Springer Gabler, Wiesbaden. https://doi.org/10.1007/978-3-658-12517-2_12
[8] AYLLÓN DÍAZ-GONZÁLEZ, J. M. (2022). Del palo a la zanahoria: sistemas de gestión ambiental, certificaciones ambientales y etiquetas ecológicas. La norma ISO 14001. Actualidad Jurídica Ambiental, 1–57. https://doi.org/10.56398/ajacieda.00011
[9] BREM, A., BREM, A., CUSACK, D. Ó., ADRITA, M. M., ADRITA, M. M., O'SULLIVAN, D. T. J., BRUTON, K., & BRUTON, K. (2020). How do companies certified to ISO 50001 and ISO 14001 perform in LEED and BREEAM assessments. Energy Efficiency, 13(4), 751–766. https://doi.org/10.1007/S12053-020-09864-6
[10] DOAN, D. T., & QIN, L.-L. (2023). Impacts of green rating systems on the economy and society. IOP Conference Series, 1204(1), 012006. https://doi.org/10.1088/1755-1315/1204/1/012006
[11] JABERI, M., & POIRIER, É. A. (2024). Mind the Gap: An Evaluation of Indicator Discrepancies between Sustainability Standards and Certifications in the Built Asset Industry. European Journal of Sustainable Development, 13(2), 141. https://doi.org/10.14207/ejsd.2024.v13n2p141
[12] MACHADO, M.C., VIVALDINI, M. & DE OLIVEIRA, O.J., 2020. Production and supply-chain as the basis for SMEs' environmental management development: A systematic literature review. Journal of Cleaner Production, 273, 123141. https://doi.org/10.1016/j.jclepro.2020.123141
[13] WANG, W. & YANG, X., 2025. Driving green technology innovation: The impact of environmental policies on manufacturing. Journal of Innovation & Knowledge, 10(2), 100684. https://doi.org/10.1016/j.jik.2025.100684
[14] ZHENG, Y., WU, Y., ZHANG, Y., MENG, X. & ZHANG, P., 2025. Greening the future: How green manufacturing shapes corporate environmental and ESG success. International Review of Financial Analysis, 100, 103994. https://doi.org/10.1016/j.irfa.2025.103994
[15] DORN, C., BEHREND, R., GIANNOPOULOS, D., NAPOLANO, L., JAMES, V., HERRMANN, A., UHLIG, V., KRAUSE, H., FOUNTI, M. & TRIMIS, D., 2016. A Systematic LCA-enhanced KPI Evaluation towards Sustainable Manufacturing in Industrial Decision-making Processes. A Case Study in Glass and Ceramic Frits Production. Procedia CIRP, 48, pp.158–163. https://doi.org/10.1016/j.procir.2016.03.146
[16] SINGH, K. & SULTAN, I.A., 2018. Modelling and Evaluation of KPIs for the Assessment of Sustainable Manufacturing: An Extrusion process case study. Materials Today: Proceedings, 5(2, Part 1), pp.3825–3834. https://doi.org/10.1016/j.matpr.2017.11.636
[17] KHANNA, N., WADHWA, J., PITRODA, A., SHAH, P., SCHOOP, J. & SARIKAYA, M., 2022. Life cycle assessment of environmentally friendly initiatives for sustainable machining: A short review of current knowledge and a case study. Sustainable Materials and Technologies, 32, e00413. https://doi.org/10.1016/j.susmat.2022.e00413
[18] ALJAMAL, D., SALEM, A., KHANNA, N. & HEGAB, H., 2024. Towards sustainable manufacturing: A comprehensive analysis of circular economy key performance indicators in the manufacturing industry. Sustainable Materials and Technologies, 40, e00953. https://doi.org/10.1016/j.susmat.2024.e00953
[19] VIJAYA, A., MEISTERKNECHT, J.P.S., ANGREANI, L.S. & WICAKSONO, H., 2025. Advancing sustainability in the automotive sector: A critical analysis of environmental, social, and governance (ESG) performance indicators. Cleaner Environmental Systems, 16, 100248. https://doi.org/10.1016/j.cesys.2024.100248
[20] GAUTAM, A., KHAN, Z.A., GANI, A. & ASJAD, M., 2025. Identification, ranking and prioritization of Key Performance Indicators for evaluating greenness of manufactured products. Green Technologies and Sustainability, 3(1), 100114. https://doi.org/10.1016/j.grets.2024.100114
[21] WANG, X., ZHANG, H. & SONG, J., 2009. Multi-objective decision-making and combination evaluation of green manufacturing enterprises. In: 2009 International Conference on Information Management, Innovation Management and Industrial Engineering. [online] IEEE, pp.nestr. https://doi.org/10.1109/ICIII.2009.611
[22] BREM, A., CUSACK, D.Ó., ADRITA, M.M., O'SULLIVAN, D.T.J. & BRUTON, K., 2020. How do companies certified to ISO 50001 and ISO 14001 perform in LEED and BREEAM assessments? Energy Efficiency, 13, pp.751–766. https://doi.org/10.1007/s12053-020-09864-6
[23] SHAHBAZI, S., KURDVE, M., ZACKRISSON, M., JÖNSSON, C. & KRISTINSDOTTIR, A.R., 2019. Comparison of four environmental assessment tools in Swedish manufacturing: A case study. Sustainability, 11(7), 2173. https://doi.org/10.3390/su11072173

Ján KOPEC[1], Miriam PEKARČÍKOVÁ[2], Juraj KOVÁČ[3], Erik VARJÚ[4]

INTEGRATING SENSORS, ROBOTICS, AND ARTIFICIAL INTELLIGENCE IN A LABORATORY LEARNING SYSTEM

Abstract

This paper presents the development and implementation of a laboratory-based learning system using the AI-Hub Navigation Kit to integrate sensing, robotics, and artificial intelligence into hands-on learning. The solution includes an Arduino MEGA 2560 as a control unit that interacts with various sensors, actuators, and the WLKATA Mirobot robotic arm. The project designed and automated a conveyor system using ultrasonic sensors, LED signaling, and motion control algorithms. This approach allows students to learn the principles of mechatronics, automation, and industrial artificial intelligence through experiential learning.

Key words: robotics, sensors, automation, Arduino MEGA 2560

1. INTRODUCTION

The AI-Hub Navigation Kit is an innovative and comprehensive educational solution specifically designed for students, educators, and technology enthusiasts who want to dive into the world of Arduino, sensors, and artificial intelligence. This kit is a practical bridge between theory and real-world implementation of advanced technologies, in the form of progressively graded projects.

Starting with a simple setup of the development environment and the basics of microcontroller programming, the user will learn how to work efficiently with sensors and electronic components. This is followed by more advanced concepts such as machine learning, sensor data processing, and the creation of intelligent control systems.

The AI-Hub Navigation Kit aims to lower the barriers to entry into AI and electronics by offering easy-to-understand tutorials, pre-made libraries, and interactive examples. The kit encourages the development of critical thinking, creativity, and practical skills that are essential in STEM fields today. It is ideal for school labs, after-school clubs, and individual self-study.

[1]Ing. Ján Kopec, Technical University of Košice, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, jan.kopec@tuke.sk, (corresponding author)
[2]doc. Ing. Miriam Pekarčíková, Technical University of Košice, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, miriam.pekarcikova@tuke.sk
[3]doc. Ing. Juraj Kováč, Technical University of Košice, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, juraj.kovac@tuke.sk

2. CONSULE MODULE ARDUINO MEGA 2560

The console includes: one multifunctional extender box for the robotic arm, one main controller (MEGA 2560), one built-in air pump, one green LED, one red LED, one green button, one red button, one rotary potentiometer, one joystick module, one infrared detection module, one color recognition module, one built-in voice recognition module, one built-in voice announcement module, one IIC expansion module, one gesture recognition module, and one vision module.

The AI-Hub Navigation Kit console is a comprehensive platform designed to support hands-on learning in robotics, automation, and artificial intelligence. It includes several components that allow students to develop a wide range of skills in mechatronics, sensing, and human-machine interaction.

This equipment makes the console a powerful tool for developing practical skills and understanding complex systems that are commonly used today in industry, research, and development of intelligent technologies.

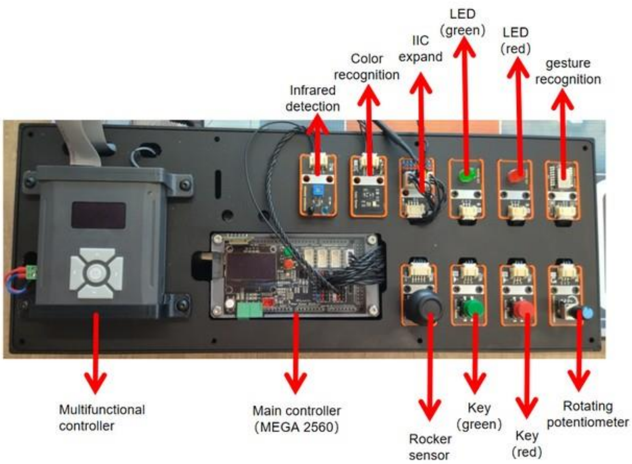


Fig. 1. Arduino Mega 2560 and AI modules

WLKATA's MEGA 2560 expansion board is an advanced development platform designed specifically for the needs of smart factories and teaching advanced technologies. It features high flexibility, broad connectivity, and the ability to efficiently manage complex systems.

This board supports communication between UART and RS-485 interfaces, enabling reliable data transfer in industrial environments and easy integration into existing systems. Its features make it ideal for task allocation and coordinated control of multiple Mirobot-type robotic arms, opening possibilities for simulations of real industrial processes.
The board is equipped with a range of integrated components that enhance its functionality and interactivity.

This expansion board greatly facilitates prototype development, algorithm testing, and the implementation of educational projects. Its versatile design makes it an ideal solution for students, researchers, and developers working in robotics, automation, and the Internet of Things (IoT).

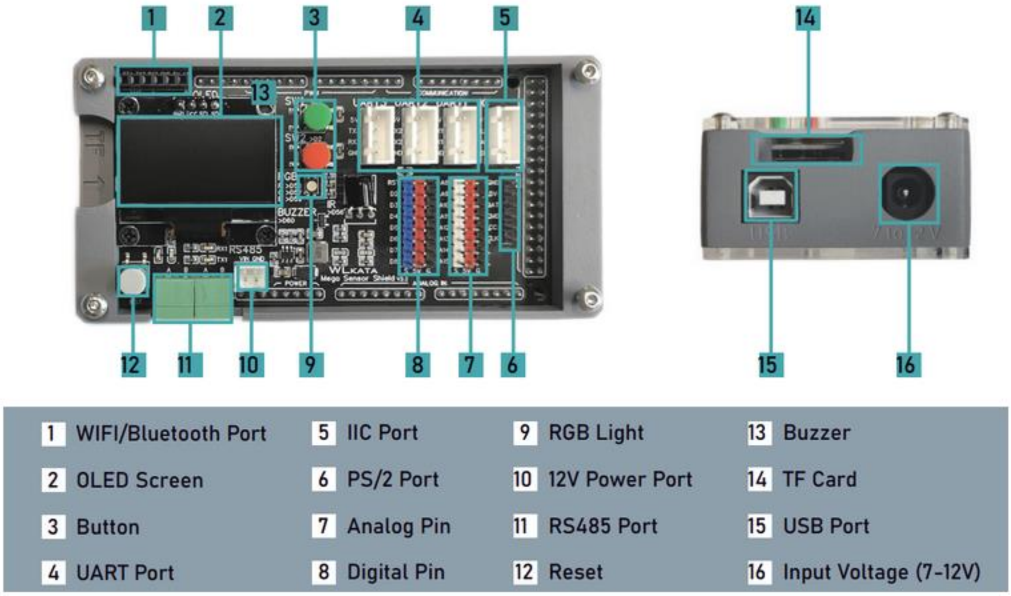


Fig. 2. Schematic diagram of MEGA 2560

3. UART COMMUNICATION PROTOCOL

UART communication protocols are widely used in industrial settings to enable efficient data transfer and synchronization between devices. They play a crucial role in facilitating seamless communication within industrial systems. UART protocols find applications in various areas such as industrial automation, connecting Human-Machine Interfaces (HMIs) to control systems, data logging and monitoring, network communication, and device configuration. In industrial automation, UART enables real-time data exchange between sensors, actuators, and controllers. It also facilitates the connection of HMIs to control systems, allowing operators to monitor and control industrial processes. Moreover, UART protocols are utilized for data logging, network communication, and device configuration, contributing to efficient data transfer, centralized control, and enhanced system performance in industrial environments.

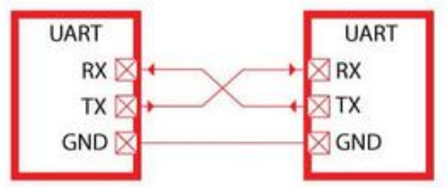


Fig. 3. AURT Communication Introduction

4. APPLICATION IN THE LABORATORY

After modelling the conveyor in SolidWorks and then printing all the components using a 3D printer, we focused on its drive and automation. A DC motor was used to set the conveyor in motion, which is controlled by an Adruino Mega 2560 microcontroller, we also used a 2x ultrasonic sensor to detect the component and an LED semaphore to signal the movement of this conveyor.

Fig. 4. Printed conveyor belt with ultrasonic device

In our case, we used this Arduino Mega 2560 board to power the mentioned DC motor, two ultrasonic sensors, and LED semaphore, which we programmed according to our designed motion and functionality in the Arduino IDE program.
The program was designed in such a way that the movement of the conveyor is influenced by two ultrasonic sensors, one located at the beginning of the conveyor belt

as the input sensor and the other sensor at the end of the conveyor belt which is the output sensor.

The main objective of the developed program is to automate the movement of the conveyor belt based on the detection of components using two ultrasonic sensors. This program has been programmed in Arduino IDE environment and is designed to demonstrate the basics of automated sorting or moving of objects in a manufacturing process.
The program controls the stepper motor that drives the belt, and also monitors the input and output of objects (parts) using HC-SR04 ultrasonic sensors. When an object is detected at the input (right sensor) at a specified distance, the belt starts automatically. The belt movement continues until the output (left) sensor detects the same object, which means that the part has reached the end of the conveyor.
In addition to the belt movement itself, the program also controls an LED semaphore that serves as a visual indicator of the current status of the entire system.

```
const int stepsPerRevolution = 2048;
const int motorSpeed = 10;
Stepper myStepper(stepsPerRevolution, 8, 10, 9, 11);
```

Fig.5. Stepper motor control

We also declare the pins on which the ultrasonic sensors will be connected (TRIG and ECHO for input and output), as well as the pins for controlling the LEDs

```
const int trigIn = 4;
const int echoIn = 5;
const int trigOut = 6;
const int echoOut = 7;

const int ledRed = 22;
const int ledYellow = 23;
const int ledGreen = 24;
```

Fig. 6. Pin declaration of ultrasonic sensors and LED semaphore

The software part of this thesis represents a key component of the entire automated conveyor belt solution. Using the Arduino IDE development environment, we have created a robust control system that responds in real time to the information obtained from the HC-SR04 ultrasonic sensors. We connected these sensors to an Arduino Mega 2560 microcontroller board, where they were configured via digital pins as TRIG and ECHO. Their task was to reliably detect the presence of a component at both the infeed and outfeed of the conveyor belt, with the distance up to which detection was taken into account being manually set to 8 cm.

5. CONCLUSION

The result of this paper is the design, implementation, and functional verification of an automated workstation that includes a conveyor belt, sensors, an Arduino-based control system, and WLKATA Mirobot robotic arms. All stages of the development were successfully handled as part of the solution - from the design of the mechanical parts in the SolidWorks environment, through 3D printing of the components, to programming and implementation of the control logic.

The conveyor belt was designed with an emphasis on modularity and reliable component handling. Belt control using ultrasonic sensors and visual signalling by LED modules contributes to efficient and safe system operation. WLKATA Mirobot robotic arms have been deployed for handling parts at different stages of the production process, using different modes of movement and control.

Acknowledgements

This article was prepared within the framework of the grant projects APVV-17-0258 Application of digital engineering elements in innovation and optimization of production flows, APVV19-0418 Intelligent solutions to increase the innovative capacity of enterprises in the process of their transformation into smart enterprises. KEGA 020TUKE-4/2023 Systematic development of competence profile of industrial and digital engineering students in the process of higher education. VEGA 1/0508/22 "Innovative and Digital Technologies in Manufacturing and Logistics Processes and Systems", KEGA 003TUKE-4/2024 Innovation of the profile of industrial engineering graduates in the context of required knowledge and specific competences for research and implementation of intelligent systems of the future and VEGA 1/0231/24 Optimization of a digital factory system using a digital twin.

References

[1] PETRÁŠ, I. a kol. Priemyselná automatizácia a riadenie procesov. Košice: TU Košice, 2017. ISBN 978-80-553-3029-9.
[2] KOVAČIČ, Z. – LÁNCOS, G. Automatizácia a riadenie technologických procesov. Bratislava: STU v Bratislave, 2013. ISBN 978-80-227-3917-0.
[3] ČAPKOVÁ, D. a kol. Základy senzoriky. Brno: Vysoké učení technické v Brně, 2019. ISBN 978-80-214-5754-1.
[4] KOVÁČ, J. a kol. Robotika vo výrobe. Bratislava: STU v Bratislave, 2011. ISBN 978-80-227-3523-3.
[5] TREBUŇA, Peter, Miriam, PEKARČÍKOVÁ, Marek, KLIMENT, Jozef, TROJAN. METÓDY A SYSTÉMY RIADENIA VÝROBY V PRIEMYSELNOM INŽINIERSTVE. Košice: TU v Košiciach, Strojnícka fakulta: Univerzitná knižnica, 2019. ISBN 978-80-553-3280-2.
[6] TREBUŇA, Peter, KLIMENT, Marek, MARKOVIČ, Jaromír. PLM and its benefits and use in the management of complex business activities in the planning and optimization of production activities, 2013. In: Manažment podnikov. Roč. 3, č. 2 (2013), s. 53-56. - ISSN 1338-4104
[7] TREBUŇA, Peter, PEKARČÍKOVÁ, Miriam, KOVÁČ, Juraj, TROJAN, Jozef, KOPEC, Ján: CAD Software Simulations in Industrial Engineering, 1. vyd., Stüttinghauser Ringstrasse : RAM-Verlag - 2023. - 290 s. [print]. - ISBN 978-3-96595-035-1.
[8] GEBHARDT, A. – HÖTTER, J.-S. Additive Manufacturing: 3D Printing for Prototyping and Manufacturing. Munich: Hanser Publishers, 2016. ISBN 978-1-56990-582-1.
[9] GIBSON, I. – ROSEN, D. – STUCKER, B. – KHORASANI, M. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. 3rd ed. Cham: Springer, 2021. ISBN 978-3-030-56126-0.

Dávid KOMAČKA[1], Martin KRAJČOVIČ[2], Marta KASAJOVÁ[3]

SOFTWARE SUPPORT FOR DESIGN, SIMULATION AND OPTIMIZATION OF PRODUCTION AND LOGISTICS SYSTEMS

Abstract

The paper describes current approaches to design, simulation and optimization of manufacturing and logistics systems with an emphasis on the use of digital enterprise tools. The main objective is to introduce the potential of software support, including RTLS technology and the concept of digital twin as essential elements of an intelligent manufacturing system.

Key words: digital twin, real time location systems, simulation models

1. INTRODUCTION

The Fourth Industrial Revolution brings the need for flexible and adaptive management of production and logistics systems. Designing these systems is no longer just a matter of static drawings and capacity calculations but requires a dynamic approach that reflects changing conditions in real time. The integration of software tools, digital twins and technologies such as RTLS (Real-Time Locating Systems) enable companies to streamline processes, minimize losses and increase competitiveness.
The current business environment emphasizes the need for modern technology integration in smart manufacturing systems [1].
Digital design and the use of digital twins in business processes play a key role in creating virtual counterparts of physical systems through which monitoring, planning and optimization can be achieved [2, 3].
RTLS technology plays an important role in data collection and localization. RTLS is defined as a method of determining the exact location of an object in a defined space, allowing detailed tracking of material flow. RTLS allows to increase supply chain efficiency and prevent collisions [4, 5].

[1] Dávid Komačka, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26, Zilina, Slovakia, david.komacka@fstroj.uniza.sk
[2] Martin Krajčovič, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26, Zilina, Slovakia, martin.krajcovic@fstroj.uniza.sk
[3] Marta Kasajová, Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26, Zilina, Slovakia, marta.kasajova@fstroj.uniza.sk

2. METHODS AND METHODOLOGY

The experiment uses a combination of qualitative and technical-analytical methods aimed at developing, testing and evaluating solutions for the intelligent design of manufacturing and logistics systems. The procedure consists of the following key steps:

1.1 Production layout analysis

Based on the provided technical drawings and data obtained from 3D scans, a detailed comparison between the planned layout and the actual physical layout is conducted. The use of 3D scanning technology ensures high-precision spatial data, which significantly reduces the likelihood of errors or discrepancies during both the design and implementation phases of layout modifications. This approach enhances the reliability of the planning process by enabling the identification and correction of potential deviations at an early stage, thereby supporting more efficient and accurate execution of changes in the physical environment.

1.2 Digital model creation

Using software solutions, a model of the production-logistics system is created. The model contains modules for human resources planning, material flows, work cycles and evaluation of layout variants.

1.3 RTLS data integration

In collaboration with the RTLS data processing platform, real-time location data captured by the RTLS infrastructure is seamlessly integrated into the digital model [6]. This integration enables a dynamic and data-driven representation of the operational environment. The collected location data serves as a critical input for several advanced analytical functions, including the identification of bottlenecks in material or personnel flow, the generation of heat maps to visualize movement patterns and space utilization, and the continuous real-time monitoring of equipment usage. By leveraging this data, organizations can gain valuable insights into operational inefficiencies, improve decision-making, and support the optimization of internal logistics processes.

1.4 Simulation and optimization

What-if simulations and decision impact analyses are performed on the developed model. The model allows us to predict the consequences of integrating the proposed changes without interfering with the real environment. Based on the results, the parameters of production and logistics processes can be adjusted.

1.5 Automatic update of models

Through the introduction of techniques such as process mining from MES and RTLS logs, simulation models are continuously updated [8]. The use of this form of adaptive simulation contributes to greater system flexibility and allows for real-time optimization.

The figure illustrates the principle of linking a physical manufacturing system with its digital model - the so-called digital twin - to achieve automatic creation and updating of simulation models.
This concept is based on the current needs of modern manufacturing companies to react quickly, flexibly and autonomously to changes in the environment.
The figure reflects a cyclical and autonomous adaptation process that minimizes the need for manual intervention in model building while providing the enterprise with the ability to make immediate and data-driven decisions [7].
This approach is particularly effective in environments with high production variability, short lead times and flexibility requirements, such as those typical of Industry 4.0 intelligent manufacturing systems.

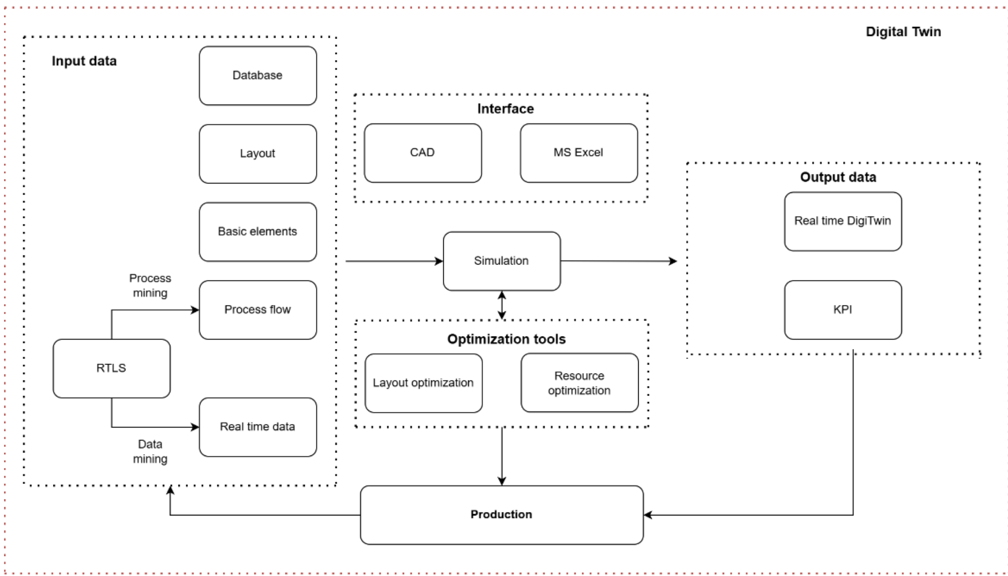


Fig. 1 Automating the creation of simulation models through a digital twin (Ruppert, 2021)

3. RESULTS AND DISCUSSION

The results of applied research and analytical investigations have shown that the use of digital tools in the processes of design, simulation and optimization of production and logistics systems leads to a significant increase in efficiency, transparency and adaptability of the enterprise to changes in the environment.

A key benefit of the digital twin is the creation of a virtual representation of physical entity, which allows for a systematic analysis of the production and logistics flow before physical changes are implemented. Such a representation includes the spatial arrangement of production elements, workplaces and transport routes, as well as the functional and technological links between them. Based on a thorough analysis of the relationships between workplaces, material flows and the frequency of transfers, it is possible to design optimal layout variants. These variants are then tested using simulation experiments to identify bottlenecks, inefficient operations or potential conflict zones.

An important aspect of this approach is the integration of real data from operations, from location and production systems, which provide an accurate and up-to-date picture of the status and evolution of the systems in real time. These data serve as inputs for the creation of digital twins - dynamic models that reflect the real configuration and behavior of the system. This allows accurate predictive scenarios to be created, their impact on system performance to be verified and decisions to be made based on objective information. The following figure depicts milk run heath maps in digital twin.

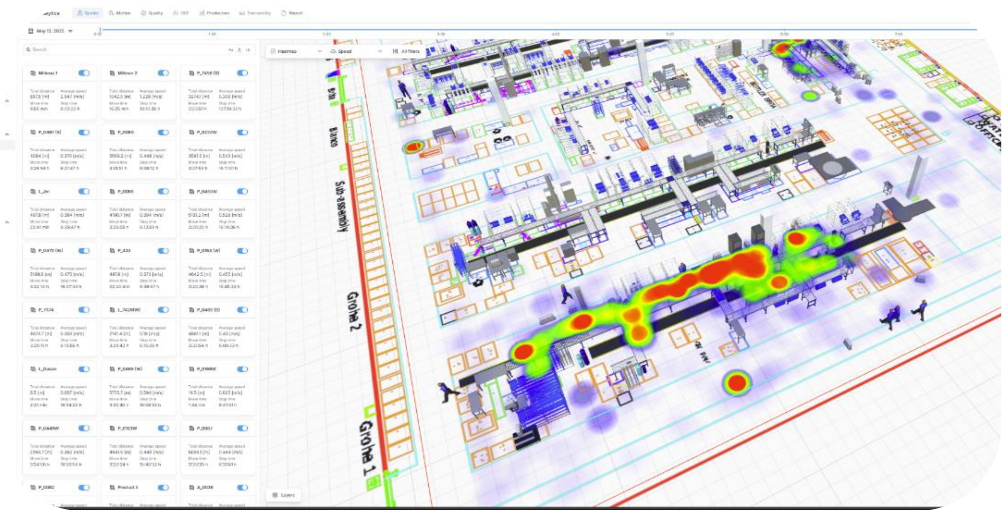


Fig. 2 Digital Twin Environment (Authors, 2025)

Integration of location data into simulation models enables detailed visualization of the movement of materials, equipment and personnel. This approach provides the ability to generate analytical outputs such as load heat maps, time analyses of movements in individual zones, or identification of downtime and inefficient moves. The insights gained are then used as a basis for optimization measures - for example, adjusting logistics routes, reorganizing workplace layouts or changing the planning of production cycles.

An important advantage is the possibility of continuous and automatic updating of simulation models based on real operational data. Such autonomous updating eliminates the need for manual interventions in the models and ensures that they are up to date in a dynamically changing environment. This gives businesses the flexibility to react to unexpected situations such as equipment failures, changes in demand or constraints in logistics capacity, and to test alternative solutions immediately.

Discussion of the results shows that linking digital models with real production data sets a new standard in the planning and management of production and logistics systems. At the same time, however, it places increased demands on the integration of data sources, the quality of input information and interoperability between different information systems. The results confirm that companies implementing this approach are able not only to optimize existing processes but also to strategically plan future changes based on simulated predictions.

4. CONCLUSION

The aim of the paper was to highlight the importance and potential of new approaches to design, simulation and optimization of production and logistics systems in the conditions of smart manufacturing enterprises [9]. The results showed that traditional, static design methods are currently inadequate to cope with the complexity and dynamics of modern manufacturing environments. The advent of Industry 4.0 technologies requires the use of digital tools that allow us to model, visualize and predict the behavior of systems in real time [10].

A key benefit of digital twin is the link between the real physical world and its virtual representation. The creation of a digital twin that is continuously updated based on data from sensing, location and information systems is an important tool for increasing the flexibility, efficiency and reliability of manufacturing and logistics operations. Such a link also allows decisions to be tested before they are implemented, significantly reducing the risk of errors and costs associated with inappropriate interventions in real operations.

Another important finding is the possibility of using process data mining and automatic model updating techniques, which contribute to reducing dependency on manual inputs and make planning and management more efficient in an environment where conditions change frequently. The results show that combining simulation models with data from location and production systems leads to a deeper understanding of real-world processes and allows decisions to be made based on evidence rather than guesswork

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0150/24.
This work was supported by the KEGA Agency under the contract no. 013ŽU-4/2025.

References

[1] GREGOR, M., MAGVAŠI, P., (2013) Inteligentné výrobné systémy. Žilinský model Produktivita a inovácie. 14. 31-37.
[2] KRAJČOVIČ, M., (2020) Digitálne projektovanie výrobných a logistických systémov. Žilina: EDIS. 82s. ISBN 978-80-554-1747-9
[3] SVITEK, R. (2021) Návrh metodiky projektovania logistického systému v prostredí digitálneho dvojčaťa. Žilinská univerzita v Žiline. Dizertačná práca. 128s.
[4] CWIKLA, G., ET AL. (2018) The initial considerations and tests on the use of real time locating system in manufacturing processes improvement. In: IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2018. p. 042013, DOI: 10.1088/1757-899X/400/4/042013
[5] GREGOR, M., et al. (2009) Digital factory. Journal of Automation Mobile Robotics and Intelligent Systems, 3.3: 123-132. Available at: https://www.jamris.org/index.php/JAMRIS/article/view/28/28
[6] ŠINKO, S., MARINIČ, E., POLJANEC, B., OBRECHT, M., GAJŠEK, B. (2022) Performance-Oriented UWB RTLS Decision-Making Approach. Sustainability 2022, 14, 11456, DOI: 10.3390/su141811456
[7] TRAN, T., RUPPERT, T., ABONYI, J., (2021) Indoor positioning systems can revolutionize digital lean. Applied Sciences, 11.11: 5291, DOI: 10.3390/app11115291

[8] HAMMERIN, K., STREITENBERGER, R., (2019) RTLS—The Missing Link to Optimizing Logistics Management, Jönköping University, Production Systems: Jönköping, Sweden

[9] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research

[10] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

Milan MARČAN[1], Radovan FURMANN[2], Dávid KOMAČKA[3]

DYNAMIC ROUTING AND REAL-TIME DECISION-MAKING OF AGVS

Abstract

This article focuses on comparing static and adaptive routing of Automated Guided Vehicles (AGVs) in a simulation environment. Our objective was to explore how the system behaves under traditional fixed routing and how it adapts when AGVs make decisions based on real-time traffic load. We tested both approaches using a simulation model of a newly built battery manufacturing plant. The simulation method proved to be a highly useful tool for finding optimized solutions without physical intervention while allowing a detailed comparison of performance metrics.

Key words: simulation, adaptive routing, digital twin, AGV

1 INTRODUCTION

Simulation is a powerful analytical method used to model, analyze, and evaluate the performance of complex systems. [1] In industrial engineering and logistics, it allows researchers and decision-makers to recreate real-world operations in a virtual environment, where they can safely test hypotheses, evaluate alternative scenarios, and identify potential issues without interrupting actual operations [1, 2].

Discrete-event simulation, agent-based modeling, and system dynamics are commonly employed techniques in this domain. One of the core advantages of simulation is its ability to visualize and quantify the impact of specific design or control changes on overall system behavior [3].

In the context of automated logistics, simulation helps in understanding the dynamic interactions between machines, operators, and system constraints. It enables experimentation with different routing strategies, fleet sizes, and scheduling algorithms, providing data-driven insights that would be difficult or costly to obtain through physical testing alone [2,3].

[1] Milan Marčan, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, milan.marcan@fstroj.uniza.sk
[2] Radovan Furmann, Ing. PhD. University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, radovan.furmann@fstroj.uniza.sk
[3] Dávid Komačka, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, david.komacka@fstroj.uniza.sk

Modern logistics increasingly relies on autonomous systems for material handling. AGVs have become a standard feature in industrial operations, ensuring the transport of components, pallets, or finished goods. A key factor in their efficiency is the routing strategy—either predetermined (static) or responsive to real-time conditions (adaptive). [4] Static routing is advantageous due to its predictability and ease of implementation but does not account for dynamic system conditions. Conversely, adaptive routing allows AGVs to respond to current route congestion, minimizing waiting times and better distributing workloads across vehicles. These two strategies have different impacts on efficiency and workflow fluidity, which can be objectively evaluated through simulation tools [4, 5].

Simulation provides an ideal environment for testing these strategies without the risks and costs of real-world trials. In this study, we analyze the differences between static and adaptive AGV routing using a digital twin of a manufacturing facility. The simulation software employed allows us to monitor performance, detect bottlenecks, and create various system configuration scenarios [4, 5].

2 SCENARIO DESCRIPTION

A detailed model (**Error! Reference source not found.**) of a battery assembly plant for electric vehicles was created for simulation purposes. The model included production lines, storage areas, charging stations, and intersections, all of which played a critical role in the AGV movement.

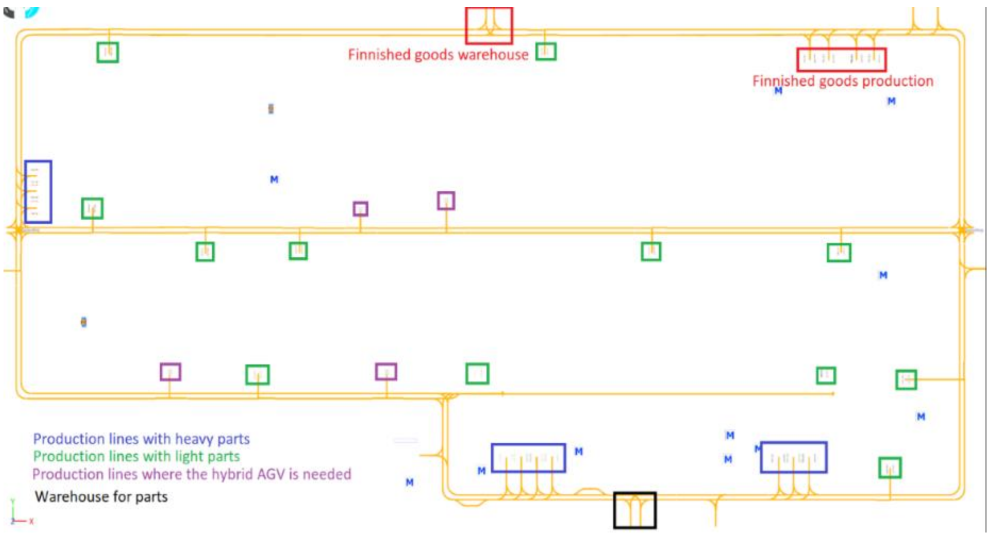


Fig. 1. Simulation model (Marčan, 2025)

In both scenarios, 15 AGVs were deployed, divided into three groups based on payload capacity. The AGV control system in both cases was compatible with the VDA5050 standard.

Scenario A - Static Routing:

AGVs followed fixed routes regardless of congestion or system changes. The paths were optimized for the shortest distance. While this type of routing is easier to plan, it proves inefficient in congested sections.

Scenario B - Adaptive Routing:

AGVs continuously assessed the occupancy of route segments and dynamically selected alternative routes with lower congestion. This real-time response to delays and blocked segments allowed the system to flexibly adapt to changing conditions.

3 SIMULATION PROCESS AND METRICS

The simulations were run over 14 simulated days and repeated 20 times for each scenario. The following metrics were tracked:

- Average transport time,
- Waiting time at intersections,
- Device utilization rate (in %),
- Route blockage rate (number of conflicts),
- Number of successfully completed tasks,
- Idle time with no assigned task.

Special attention was also given to the utilization analysis of each AGV type and the detection of bottlenecks using Sankey diagrams and heat maps of intersections. This approach enabled detailed monitoring of how real-time decision-making impacts overall system performance.

4 RESULTS AND DISCUSSION

The simulation results clearly highlighted the advantages of adaptive routing. Compared to the static scenario, there were:

- An 8.6% reduction in average transport time,
- Over 20% reduction in intersection waiting times,
- A 35% decrease in blocked intersection events,
- A 9% increase in the number of completed transport tasks.

These results are also visualized on
Fig. 2.

In addition to quantitative metrics, simulation revealed qualitative improvements, such as more balanced workload distribution among AGVs, which can extend equipment lifespan and reduce wear and tear. Simulation also allowed identification of persistent problem areas, such as inefficiently located charging stations or overly narrow transport segments. These insights are invaluable for physical infrastructure design before commissioning.

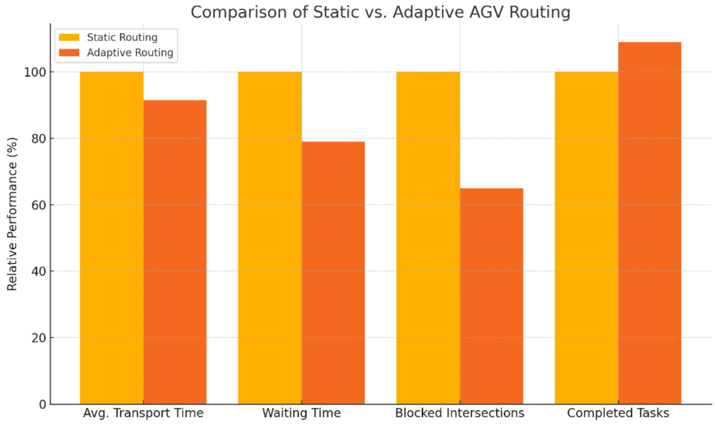


Fig. 2. Comparison graph (Marčan, 2025)

5 CONCLUSION

The comparison of static and adaptive routing in a simulation environment confirmed the benefits of adaptive strategies for effective AGV management. Simulation proved to be a key tool for testing and refining routing strategies without the need for costly real-world experiments. For modern production environments demanding high flexibility and adaptability, dynamic routing offers a path to greater efficiency, safety, and reduced operational costs. Future work can focus on evaluating various decision-making algorithms and analyzing hybrid strategies (e.g., semi-adaptive models). Integrating machine learning for traffic load prediction also appears to be a promising direction.

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0150/24.
This work was supported by the KEGA Agency under the contract no. 017ŽU-4/2025.
This work was supported by the Slovak Research and Development Agency under the contract no. APVV-21-0308.

References

[1] GRZNÁR, P., BURGANOVÁ, N., MOZOL, Š., MOZOLOVÁ, L. 2023. A Comprehensive Digital Model Approach for Adaptive Manufacturing Systems, Multidisciplinary Digital Publishing Institute, 2023, 13, 10706, doi:10.3390/app131910706.

[2] GRZNÁR, P., GREGOR, M., MOZOL, Š., MOZOLOVÁ, L., KRUMP, H., MIZERÁK, M., TROJAN, J. 2024. A Comprehensive Analysis of Sensitivity in Simulation Models for Enhanced System Understanding and Optimisation. Processes 2024, 12, 716. doi: 10.3390/pr12040716.

[3] KOVALSKÝ, M. 2018. Parametrizácia simulačných modelov pre rozvrhovanie výroby. Žilinská univerzita v Žiline. Dizertačná práca. 132s.

[4] GREGOR, M., HODOŇ, R., GRZNÁR, P., MOZOL, Š. 2022. Design of a System for Verification of Automatic Guided Vehicle Routes Using Computer Emulation. Appl. Sci. 2022, 12, 3397. DOI: 10.3390/app12073397.

[5] MIČIETA, B., Staszewska, J., Kovalský, M., Krajčovič, M.; Biňasová, V.; Papánek, L.; Antoniuk, I. 2021. Innovative System for Scheduling Production Using a Combination of Parametric Simulation Models. Sustainability 2021, 13, 9518. DOI: 10.3390/su13179518.

Marian MATYS[1], Mariana MÁCHOVÁ[2], Anna MIČIETOVÁ[3]

UTILIZATION OF GAMIFIED VR APPLICATION AT INVENT 2025 CONFERENCE

Abstract

Virtual reality (VR) offers a great connection between education and entertainment through its ability to create immersive educational games with gamification elements. This paper presents a VR application used as part of the InvEnt 2025 event to enhance the program and connect learning with entertainment.

Key words: virtual reality, education, virtual environment

1. INTRODUCTION

Virtual reality (VR) is steadily leaving the boundaries of the gaming industry. In recent years, it has also found a foothold in the field of education, especially where traditional methods are reaching their limits. Combined with entertainment elements, VR is becoming an ideal tool for creating immersive educational applications that connect entertainment with knowledge transfer [1,2]. The main advantage of VR is the ability to transport the user directly to the centre of the action. Instead of passively following an explanation, a student can walk through a virtual environment that can simulate any place or process. What would otherwise remain only theoretical information on paper suddenly turns into a personal experience. In addition, entertainment-educational VR applications can naturally increase user motivation and engagement through interactive tasks, game mechanics, gamification elements and more.
Developers are increasingly creating VR applications that are not just technological demonstrations, but real-world tools with practical uses in schools, museums, and industry [3-5]. For example, teaching anatomy in 3D space allows students to explore the human body in layers, while language courses can simulate foreign language conversations in a realistic environment.
The article presented showcases the usage of virtual reality at the InvEnt 2025 conference combining entertainment and test of knowledge.

[1] Marián Matys, Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, marian.matys@fstroj.uniza.sk
[2] Mariana Máchová, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic, mariana.machova@fstroj.uniza.sk
[3] Anna Mičietová, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Machining and Production Technologies, Univerzitná 8215/1, 010 26 Žilina, Slovak Republic, anna.micietova@fstroj.uniza.sk

2. VIRTUAL REALITY AT INVENT 2025

As a way to expand the InvEnt 2025 conference program a VR application was developed, which tests the participants' knowledge in industrial engineering and other areas. The creation of this application can be divided into four main parts covering different stages of the development, as shown in Fig. 1.

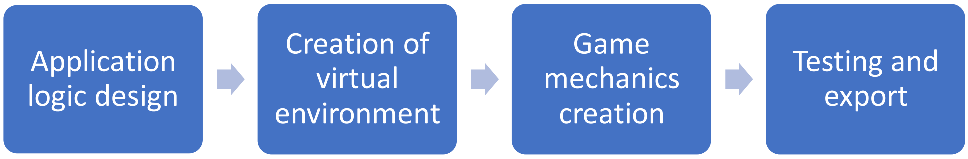


Fig. 1 Phases of development.

1.1 Application logic design

Created VR application is an immersive linear experience which can be divided into two main parts: the hike and the quiz part.
At the start, the user is placed near the top of the mountain; after getting familiar with the controls, they are tasked with climbing to the top. At the top, a small walk follows until arriving at the drawbridge. To get to the other side (the main goal of the game), five questions need to be answered. However, the user can make only one mistake. If a second mistake is made, the bridge falls apart and the user falls to the ravine and teleports to the bottom of the mountain where they can choose to start again. The entire logic is shown in Fig. 2.

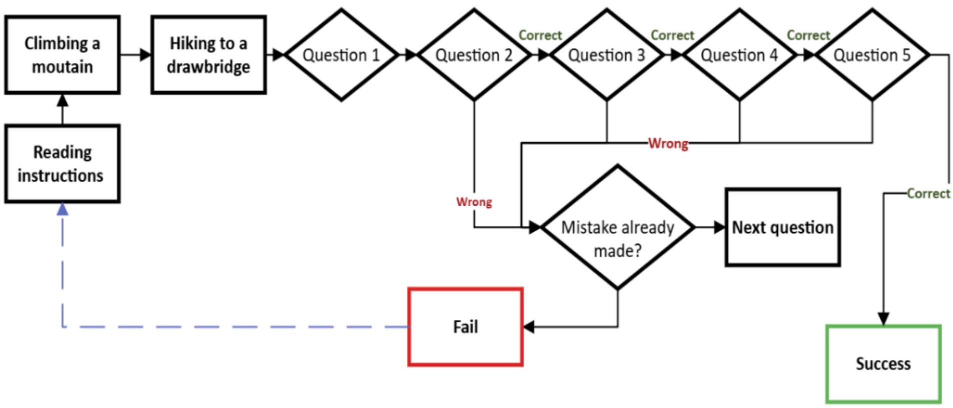


Fig. 2 Logic of the application.

1.2 Creation of virtual environment

The InvEnt 2025 conference was held in the High Tatras, so it was fitting that a game also matched this environment. Therefore, the scene consisted entirely of mountains. Fig. 3 shows the created environment. Various objects were added that will be used for interactions or to enhance the environment. For example, climbing stones were added, which were used to build the climbing minigame (Fig. 3).

Fig. 3 Virtual environment.

1.3 Game mechanics creation

With prepared environment, prepared asset could be used to script designed mechanics. Firstly, the stones shown in fig. 4 were turned into interactable objects with a climbing script added. Touching them triggered the climbing function in which user needed to replicate climbing movement to get on top of the mountain.

The main mechanic was the quiz. Five questions from different categories while users could only make one mistake. To prevent repetition, the database of questions was created in both Slovak and English language. Moreover, on every launch five questions from this database were randomly picked. Every question had four possible answers with one being always correct. Asked categories included industrial engineering, InvEnt conference trivia, High Taras trivia and more. Fig. 4 shows the randomly generated questions on a drawbridge.

If the drawbridge is successfully crossed, the user is declared as winner. The goal of the game and its controls were explained in the form of floating text that was added as a part of the UI–user interface. A laser pointer coming from the user's hand was used as a tool to interact with the created UI.

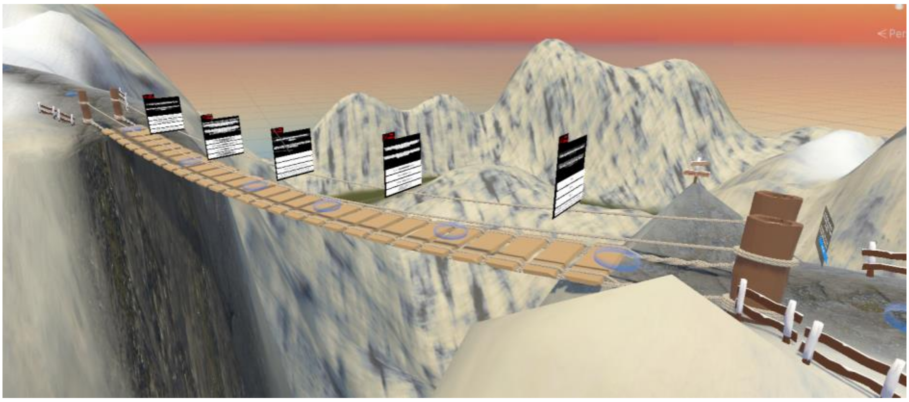


Fig. 4 The quiz.

1.4 Testing and export

In the final stages, the application was tested (fig. 5) to correct any shortcomings and fine-tune the experience. Two types of locomotion were tested, teleport and smooth movement. In the end, both were kept in the game.

Fig. 5 Testing of the application.

3. CONCLUSION

In conclusion, virtual reality offers a big potential for connecting educational applications with entertainment. At first, the creation of such applications may be challenging, but with experience, it enables creators to develop immersive and educational experiences. The application presented at the InvEnt 2025 conference shows its potential to not only entertain but also to educate.

Acknowledgements

This work was supported by the KEGA Agency under the contract no. 001ŽU-4/2024.
This work was supported by the KEGA Agency under the contract no. 005ŽU-4/2024.

References

[1] P. HOŘEJŠÍ, J. POLCAR, L. ROHLÍKOVÁ, "Digital Factory and Virtual Reality: Teaching Virtual Reality Principles with Game Engines" in Virtual Learning (Dragan Cvetkovic eds.), pp. 155-174, Rijeka/Croatia: InTech, 2016. doi: 10.5772/65218.

[2] M. GREGOR, R. HODOŇ, V. BIŇASOVÁ, Ľ. Dulina, M. Gašo, "Design of simulation-emulation logistics system", MM Science Journal, vol. 2018, pp. 2498-2502, 2018.

[3] B. HORVÁTHOVÁ, Ľ. DULINA, I. ČECHOVÁ, et al, "Data collection for ergonomic evaluation at logistics workplaces using sensor system", Transportation Research Procedia, vol. 40, pp. 1067-1072, 2019.

[4] M. BUČKOVÁ, R. SKOKAN, M. FUSKO, R. HODOŇ, "Designing of logistics systems with using of computer simulation and emulation". Transportation Research Procedia, vol. 40, pp. 978-985, 2019.

[5] R. SÁSIK, M. HALUŠKA, R. MADAJ, M. GREGOR, P. GRZNÁR, "Development of the Assembly Set for the Logistic Transport Solution" in The Latest Methods of Construction Design (V, Dynybyl, O. Berka, K. Petr, F. Lopot, M. Dub, eds.), pp. 81 – 86, Cham: Springer International Publishing, 2016. https://doi.org/10.1007/978-3-319-22762-7_13.

Branislav MIČIETA[1], Vladimíra BIŇASOVÁ[2], Honorata HOWANIEC[3]

DATA COLLECTION IN HOLONIC PRODUCTION SYSTEM

Abstract

Intelligent manufacturing systems, artificial systems, can be divided into several groups. The most common example is the division according to the chosen approach and the artificial intelligence methods used in them. The paper focuses on the functional parts that an MES system must contain to perform tasks in a holonic control system.

Key words: Data collection, Holon, Holonic systems, process

1. INTRODUCTION

Manufacturing and logistics systems are currently undergoing revolutionary changes. They are gaining new features and functionalities. We are finally beginning to view manufacturing as a holonic system. Machines, robots, and products are becoming intelligent, and advanced information and communication technologies are becoming the central nervous systems of future manufacturing [1].

Today's automatic control is mostly centralized and strictly hierarchical. This is how entire large-scale industrial networks are built today, connected to programmable controllers that also operate in a centralized mode. [2,3]

Unlike centralized systems, multi-agent and holonic systems represent a dynamic, easily expandable alternative. The system is able to respond very effectively to changes caused by the arrival of a priority order or the failure of a production unit, with its response proportional to the severity of the cause. One specific agent will attempt to solve the problem, and if it fails, it will request the cooperation of surrounding agents. The structure of production lines and production processes is not fixed in the control system structure, but is created dynamically when a new order is created. It is automatically adjusted with each change. Since the control and planning process is distributed across a larger number of computing units, the risk of instability caused by

[1] Branislav Mičieta, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Enginering, Department of Industrial Engineering, Univerzitna 1, 010 26 Zilina, branislav.micieta@fstroj.uniza.sk

[2] Vladimíra Biňasová, Ing. PhD. DiS., University of Zilina, Faculty of Mechanical Enginering, Department of Industrial Engineering, Univerzitna 1, 010 26 Zilina, vladimira.binasova@fstroj.uniza.sk

[3] Honorata Howaniec, Dr., Department of Marketing and Entrepreneurship, Faculty of Management and Transport, University of Bielsko-Biala, ul. Willowa 2, 43-309 Bielsko-Biała, hhowaniec@ubb.edu.pl

the failure of a single agent is minimized. A number of applications require distributed control. These include applications in the chemical industry or in the distribution of electricity, gas or water, where autonomous units are needed to perform many interventions in the controlled technology independently, without communication with the centre. In flexible production areas, it is sometimes necessary to replace, add, or remove certain equipment during operation, not only due to failure or maintenance, but also when changing the production plan. It is important to find a new production path as quickly as possible for each such change [4]. Holonic and multi-agent systems are a suitable solution for all these purposes.

2. METHODS AND METHODOLOGY

Soon, artificial intelligence will take over many control and decision-making activities in manufacturing. Manufacturing systems will be able to learn from their previous operations [5]. Virtualization will bring about the mass deployment of sensors in manufacturing, enabling the collection of large amounts of data, which can then be used to create information, further processed, and used to create and apply new knowledge. The new manufacturing environment will maintain and operate its virtual image using Internet of Things and Cloud Computing technologies. Without intelligent and adaptive manufacturing and logistics, companies will not be able to operate effectively in the competitive environment of global markets.

To ensure cooperation between holons, it is essential to choose the right architecture for mutual communication. The most common method of communication mentioned in literature and online sources is SOA architecture, which is also frequently implemented. When implementing SOA, there are cases where meeting communication requirements is unnecessarily complicated and time-consuming, such as obtaining additional information for other resources. The concept (Fig. 1) proposes the use of REST architecture as a replacement for SOA architecture for holons whose communication layer consists of separate PCs (Raspberry PI) and their communication interface implemented via API. The API is formed by the REST framework, whose practical implementation can be represented in the PYTHON language [6]. The red colour in Fig. 1 represents the data bus between Raspberry PI and PLC, or intelligent sensor.

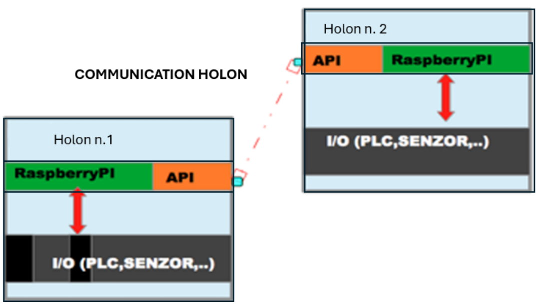


Fig. 1. The principle of communication of the concept of rest between two holons [6]

3. RESULTS AND DISCUSSION

REST (Representational State Transfer) is a way to easily create, read, edit, or delete information from a server/holon using simple HTTP calls. REST represents an interface architecture designed for distributed environments. REST was designed and described in 2000 by Roy Fielding (co-author of the HTTP protocol) in his dissertation Architectural Styles and the Design of Network-based Software Architectures.

The REST interface can be used for uniform and simple access to resources. Resources can be data as well as application states (if they can be described by specific data). Unlike the more familiar XML-RPC or SOAP, REST is data-oriented, not procedural.

The status of the application and its behaviour is expressed by a so-called resource (key resource), each of which must have a unique identifier (URL). HATEOAS (Hypermedia as the Engine of Application State) represents the status of the application determined by the URL. Other possible solutions can be obtained using links that the client receives in response from the server. A uniform approach to obtaining and manipulating the resource is defined in the form of four CRUD operations (create, read, update, delete). The resource can represent XML, HTML, JSON, SVG, PDF, whereby the client does not work directly with the resource, but with its representation.

Client/server is used to define responsibilities.

- Stateless – each request must contain all the information necessary for its execution. • CACHE – each request can be explicitly marked as “cacheable” or “non-cacheable”, which allows for a transparent increase in performance by adding a cache between the client and server.
- Code-On-Demand – client functionality can be extended with code sent by the server (e.g., JavaScript).
- Layering – allows for the composition of service-providing layers to increase variability (cache, transformation, load balancing, etc.). There are, of course, other approaches to distributed architecture, such as RPC (Remote Procedure Call).

In general, we can say that the difference between REST and RPC is twofold:

- the semantics of operations and what is distributed,
- the semantics of operations in REST is finite and consists only of CRUD (create, read, update, delete) in a given resource.

4. CONCLUSION

Artificial intelligence, the application of knowledge systems, and intelligent holonic solutions will certainly be new sources of productivity growth in the next stages of development [7,8]. Behind the closed doors of research laboratories, turbulent and secret research is currently underway in the field of humanoid robots, which will take over the entire service area in factories [9,10].

REST services are not an ideal solution for all cases. Although they draw on simplicity and resemble classic websites, there are areas where their use is not as straightforward as with SOAP services. These include, for example, various steps in the communication process between the client and the server. Examples include the implementation of a single transaction across multiple services, asynchronous operations, or complex security and communication requirements that can be handled by WS-* standards. Nevertheless, REST architecture seems to be more efficient than SOA. Its main advantage is its simplicity, which is a very interesting feature in the software world, where complexity can be one of the biggest problems.

By using the programmatic and technical means described in the article, it is possible to achieve effective collection and management of a holonic production system.

Acknowledgements

This research study was supported by the project VEGA 1/0633/24 and by the project KEGA 011ŽU-4/2025.

References

[1] MIČIETA, BRANISLAV - MACEK, PETER. Development of intelligent modular quality checking system - InMoSysQC In: Digital factory management methods and techniques in engineering production. - Bielsko-Biała: Wydawnictwo Akademii techniczno-humanistycznej, 2011. - ISBN 978-83-62292-57-8. - S. 73-78.
[2] ROFÁR JÁN, - STRÁPKOVÁ, JANA: Implementation MES into intelligent manufacturing system In: TRANSCOM 2011 : 9-th European conference of young research and scientific workers : Žilina, June 27-29, 2011, Slovak Republic. - Žilina: University of Žilina, 2011. - ISBN 978-80-554-0372-4. - S. 205-208
[3] Ing. ROMAN BRÁZDA.: Výrobný informačný systém a jeho použitie [cit. 2014-1-[Online] Available: internete: <http://www.compas.cz/UserFiles/Informace/odborne_clanky/Technika-clanek-2010-10-COMES-SK.pdf >
[4] HLAVENKA, B.: Projektování výrobních systémů. Akademické nakladatelôství CERM, Brno 2005.
[5] BORKO, ĽUBOŠ: Načo slúžia Dátové služby? [online]. April 15, 2009 7:16 Available: http://blog.aspnet.sk/lubo10/archive/2009/04/15/na-o-sl-250-ia-d-225-tov-233-slu-by.aspx.
[6] HRUBANÍK, P., ROFÁR, J. 2015. Koncept zberu údajov holonického systému. ATP Journal 4/2015.
[7] Intelligent manufacturing systems. The Žilina model. Available from: https://www.researchgate.net/publication/280731448_Inteligentne_vyrobne_systemy_Zilinsky_model [accessed Jun 04 2025].
[8] GREGOR, M., MAGVAŠI, P. 2013. Inteligentné výrobné systémy. Žilinský model. ResearchGate. Available: https://www.researchgate.net/publication/280731448_Inteligentne_vyrobne_systemy_Zilinsky_model#fullTextFileContent
[9] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research
[10] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

Lucia MOZOLOVÁ[1], Patrik GRZNÁR[2], Štefan MOZOL[3]

INGTEGRATION OF DEEP REINFORCEMENT LEARNING NEURAL NETWORKS INTO INDUSTRIAL PRACTICE

Abstract

This article analyzes the use of deep reinforcement learning (DRL) in combination with simulation metamodeling to optimize the Kanban system in production processes. The proposed DRL model, based on the Deep Q-Network algorithm, was tested in the Tecnomatix Plant Simulation environment. The results showed a 25% reduction in lead times and inventory by 30% compared to traditional methods such as classic Kanban and MRP. The research contributes to the automation of meta-modeling and supports the goals of Industry 5.0, including sustainability. Future research should validate the model in a real-world environment and integrate it with IoT technologies.

Key words: Deep Reinforcement Learning, Neural Network, Industrial Processes, Process Optimization

1. INTRODUCTION

The current manufacturing environment is undergoing constant change and requires manufacturing processes that are efficient and can also adapt very quickly. Technologies such as simulation, artificial intelligence (AI) and the Internet of Things (IoT) are becoming increasingly necessary for optimizing production in real time. Although simulation has good results in analysing and testing production, it is still often time-consuming and computationally intensive. A suitable alternative is simulation metamodeling, which can simplify complex simulations, although they often lack flexibility and require manual adjustments [1,2].

This is where neural networks (ANNs) that can autonomously learn from data and adapt to changing assumptions come in. Deep reinforcement learning (DRL) emerges as an effective method for dynamic optimization of manufacturing processes, including Kanban system management.

[1] Lucia Mozolová, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, lucia.mozolova@fstroj.uniza.sk
[2] Patrik Grznár, assoc. prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, patrik.grznar@fstroj.uniza.sk
[3] Štefan Mozol, Ing. PhD. University of Žilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215, 010 26 Žilina, Slovakia, stefan.mozol@fstroj.uniza.sk

This work delves into how ANNs, and DRL, can be integrated into production management to boost both efficiency and flexibility. We will outline a DRL model architecture tailored for optimizing industrial processes, explain its learning cycle, and explore the anticipated advantages, such as shorter lead times, reduced inventory levels, and contributions to sustainability. It's worth noting that Industry 4.0 champions digitization and automation using tools like IoT, AI, and digital twins to drive up productivity and cut costs [3,4]. Looking ahead, Industry 5.0 places a greater emphasis on sustainability and resilience, incorporating environmental objectives such as carbon neutrality [5]. Both simulation metamodeling and DRL are key to enabling dynamic process control, which helps manufacturers tackle fluctuating demand and disruptions in the supply chain, thereby fostering more flexible and competitive operations [6].

Simulation remains a cornerstone for analysing production systems and testing out different scenarios without interfering with ongoing operations [7]. However, its significant computational demands can be a bottleneck for real-time applications [4]. Metamodeling provides a route to simplify these complex simulations, allowing for quicker decisions, but this simplification can come at the cost of flexibility, often needing manual fine-tuning [6]. DRL offers a pathway to automate the creation of these metamodels, thereby boosting their adaptability for tasks like the dynamic optimization of Kanban systems [8].

The core objective of this research is to fuse DRL with simulation metamodeling to refine Kanban system operations, aiming for better efficiency and greater flexibility through automated decision-making [9]. We will also explore how DRL can help cut down lead times, keep inventory to a minimum, and align with the sustainability goals set forth by Industry 5.0.

2. METHODS AND METHODOLOGY

Deep reinforcement learning (DRL) combines reinforcement learning with deep neural networks, enabling agents to learn optimal decisions in dynamic environments by maximizing cumulative rewards. Simulation metamodeling creates simplified models from simulation data, reducing computational complexity but lacking adaptability. Integrating DRL automates metamodel creation, enhancing flexibility for managing production systems like Kanban under variable demand.

The DRL model optimizes the Kanban system to control material flow and minimize inventory. Its architecture, shown in Fig. 1, uses the Deep Q-Network (DQN) algorithm with a three-layer neural network and ReLU activation. Inputs include Kanban parameters (card count, inventory, demand), and outputs are actions (adding/removing cards). The reward function minimizes lead times and inventory while ensuring smooth production. Implemented in Python with TensorFlow and simulated in Tecnomatix Plant Simulation, the model learns iteratively via experience replay, improving flexibility over static Kanban rules.

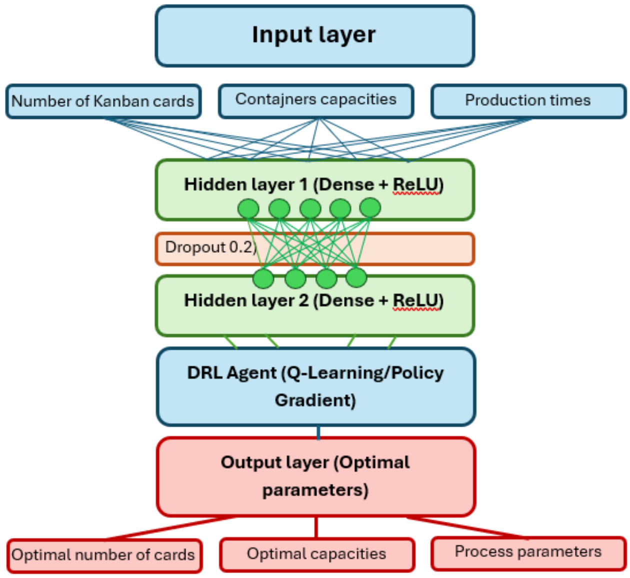


Fig. 1. Architecture of the DRL model used to optimize the Kanban system

Data for training and validating the DRL model were collected using a Simio-based production line simulation, including material flow, waiting times, inventory, and demand data. Synthetic scenarios (e.g., demand fluctuations, equipment failures) ensured model robustness. The dataset of 10,000 cycles was split into 80% training and 20% validation sets. Data were normalized to [0, 1] and cleaned to ensure neural network input consistency. The model was trained in over 100-episode iterations, with validation comparing performance (lead times, inventory) against traditional Kanban and MRP systems, as detailed in Chapter 3.

3. RESULTS AND DISCUSSION

This chapter presents the results of research focused on the implementation of deep reinforcement learning (DRL) into Kanban system management using simulation metamodeling. It analyzes the quantitative and qualitative benefits of the proposed DRL model, compares its performance with traditional production management methods, and discusses potential benefits and limitations.

The implementation of the DRL model was tested on a production line simulation model in the Tecnomatix Plant Simulation software, which represented a typical Kanban system in the automotive industry. The model optimized the allocation of Kanban cards to minimize lead times and inventory while maintaining a smooth flow of material. After 1000 training episodes, the DRL model achieved a stable decision-making policy, which was visualized in the learning cycle graph (Fig. 2).

Quantitative results showed that the DRL model reduced average lead times by 25% (from 120 minutes to 90 minutes) and inventory by 30% (from 500 units to 350 units) compared to the original Kanban system setup. These improvements were achieved by dynamically adjusting the number of Kanban cards based on simulated demand fluctuations. Qualitatively, the model showed higher adaptability to unexpected changes, such as equipment failures, where it was able to quickly restore the balance of the material flow. Tab. 1 summarizes the key performance metrics (lead times, inventory, waiting times) before and after the implementation of the DRL model, demonstrating its effectiveness in a simulation environment.

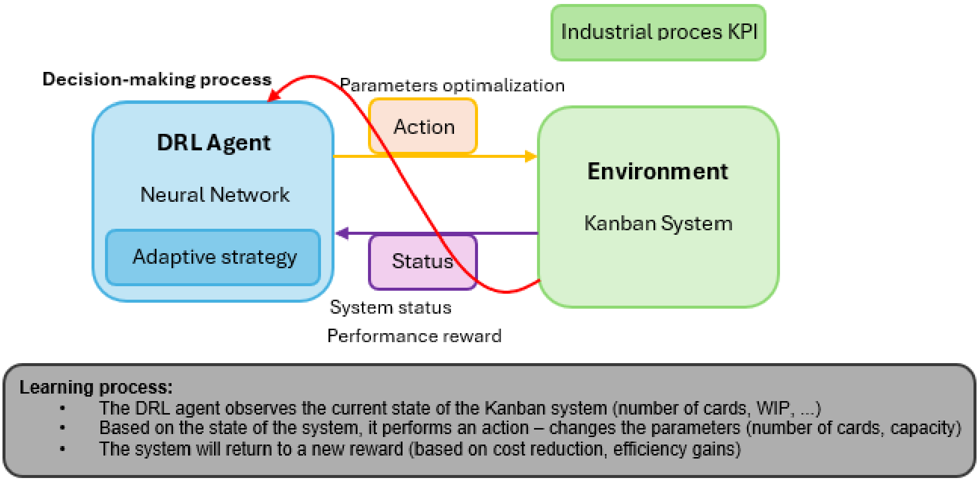


Fig. 2. DRL model learning cycle graph showing reward convergence after 1 000 episodes

Tab. 1. Comparison of performance metrics before and after implementing a DRL model

Metric	**Before DRL**	**After DRL**	**Improvement (%)**
Lead time (min)	120	90	25
Inventory (units)	500	350	30
Waiting time (min)	30	20	33

3.1 Comparison with traditional methods

The DRL model was compared with two traditional methods of production management: the classic Kanban system and the Material Requirements Planning (MRP) system. The classic Kanban system, based on static rules for the number of cards, showed less flexibility in responding to fluctuations in demand, resulting in higher inventories (500 units vs. 350 units for DRL) and longer waiting times (30 minutes vs. 20 minutes). The MRP system, although effective in planning based on anticipated demand, was unable to adequately respond to unexpected failures, causing delays in the material flow.

In contrast to these methods, the DRL model uses dynamic learning from data, which allows it to adjust the allocation of resources in real time. For example, with a simulated

20% increase in demand, the DRL model reduced wait times 15% more efficiently than MRP. The architecture of the DRL model, shown in Fig. 2, illustrates a two-layer neural network structure that processes inputs such as the number of Kanban cards, inventory status, and demand, and generates actions to optimize material flow. These results are consistent with the literature highlighting the benefits of DRLs in optimizing dynamic systems.

3.2 Discussion of benefits and limitations

The research brought several theoretical and practical benefits. From a theoretical point of view, it expands the knowledge of the integration of DRLs into simulation metamodeling, thus contributing to the development of automated production control methods. In practice, a 25% reduction in lead times and a 30% reduction in inventory indicates the potential of the DRL model for implementation in real-world manufacturing companies, such as the automotive industry, where efficiency is key. In addition, minimizing inventories promotes sustainability by reducing overproduction and waste, which is in line with the goals of Industry 5.0.

Despite these benefits, the DRL model faces limitations. The high computational demand for training (e.g. 1000 episodes per convergence) can be a barrier for businesses with limited IT infrastructure. The quality of the results depends on the availability of robust data, which requires advanced data collection systems such as IoT sensors. Another limitation is the complexity of integrating DRLs into existing ERP systems, which can increase implementation time. To overcome these challenges, a combination of DRLs with simpler statistical metamodels and testing in a real-world production environment to verify the scalability of the model is recommended.

4. CONCLUSION

Research has shown that the DRL model, designed using the Deep Q-Network algorithm (Fig. 1), effectively optimizes the Kanban system. Simulations in Tecnomatix Plant Simulation software have shown a 25% reduction in lead times and inventory by 30% compared to traditional methods such as classic Kanban and MRP. The learning cycle of the model (Fig. 2) confirmed its ability to respond dynamically to fluctuations in demand, thereby increasing the flexibility of production processes.

In practice, the DRL model allows cost reductions and overproduction, which is beneficial for the automotive industry and promotes sustainability within Industry 5.0. In theory, the research advances knowledge about the automation of metamodeling using artificial neural networks, thus contributing to the development of intelligent manufacturing systems.

Future research should test the DRL model in a real-world production environment to verify its scalability. Integration with IoT technologies and the digital twin can improve data collection and model accuracy. Exploring hybrid approaches combining DRLs with statistical methods could reduce computational effort and facilitate implementation.

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0150/24.
This work was supported by the KEGA Agency under the contract no. 017ŽU-4/2025.
This work was supported by the Slovak Research and Development Agency under the contract no. APVV-21-0308.

References

[1] GRZNÁR, P. Operations management. Lecture, University of Žilina; 2024

[2] SIEMENS. Neural network for optimization. 2025. Available on the internet: https://blogs.sw.siemens.com/tecnomatix/neural-network-for-optimization/.

[3] BAG, S. et al. (2024). Computers & Industrial Engineering, 187.

[4] GREGOR, M.; et. al. *Simulačné metamodelovanie*. Slovenské centrum produktivity, 2021. 178 s. ISBN 978-80-89333-23-3.

[5] KRENCZYK, D. Deep reinforcement learning and discrete simulation-based digital twin for cyber-physical production systems. *Applied Science*, 14(12), 2024, 24 s. ISSN 2071-1050.

[6] MOZOLOVÁ, L.; et. al. Streamlining utilisation of the assembly line using computer simulation. *Acta logistica – International Scientific Journal about Logistics*, 10(2), 2023, 165-173 s. ISSN 1339-5629.

[7] SUTTON, R. S., & Barto, A. G. (2018). Reinforcement Learning: An Introduction. MIT Press.

[8] MOZOLOVÁ, L. Projekt dizertačnej práce. Žilinská univerzita v Žiline, 2024.

[9] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research

Andrej POLKA[1], Milan GREGOR[2], Peter BUBENÍK[3]

ADAPTIVE LOGISTICS SYSTEMS FOR EFFICIENT SUPPLY

Abstract

Efficient supply through adaptive logistics represents a new approach to managing logistics processes, emphasizing rapid changes, autonomous decision-making, and flexible integration of technologies. This article describes how various elements—such as the Digital Twin, Intelligent Transport Units (IPUs), RTLS systems, and navigation solutions—can contribute to improving and streamlining material flow and the method of supply. Thanks to these elements and real-time online communication between devices, as well as integration with ERP/MES (Enterprise Resource Planning / Manufacturing Execution System) systems, the supply process becomes more efficient, reliable, cost-effective, and capable of flexibly responding to changing demands.

Key words: Adaptive Logistics Systems (ALS), IoT, Dynamic inventory management

1. INTRODUCTION

Efficient supply in business practice is not only about increasing storage capacities or rapidly investing in new inventory management technologies. Rather, it represents a comprehensive approach that utilizes modern and often advanced tools to support autonomous and flexible operation of logistics processes [1].

Adaptive logistics is based on a concept in which logistics elements (carts, transport units, conveyors) and information systems (ERP, MES) are capable of real-time communication and can respond to current needs. In practice, this means that all components of the logistics system can effectively utilize their capabilities and capacities with minimal risk of errors or downtime. For this reason, it is important that companies maintain an open approach to innovation and new technologies [2].

Given that the business environment is increasingly dynamic, industrial companies need to respond flexibly to fluctuations in demand, supply disruptions, or internal

[1] Andrej Polka, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, andrej.polka@fstroj.uniza.sk
[2] Milan Gregor, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, milan.gregor@fstroj.uniza.sk
[3] Peter Bubeník, assoc. prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, peter.bubenik@fstroj.uniza.sk

changes in production. Adaptive logistics, thanks to the use of advanced systems, contributes to the smoothness and reliability of the entire supply chain [3].

2. ADAPTIVE LOGISTICS

Adaptive logistics is an approach in which logistics processes can quickly and autonomously adjust to changes in production and market conditions. It stems from the need for greater flexibility, autonomy, and variability. This approach relies on elements such as autonomous transport vehicles, intelligent transport units, advanced control algorithms, and real-time software systems [4].

The core idea is that devices can exchange information and make local decisions without the need for centralized control, increasing the system's resilience and responsiveness. This concept builds on principles of agent-based and holonic control, supported by advanced sensors, cloud computing, and the Internet of Things (IoT), which ensure continuous data flow from the physical environment to control systems [5].

3. TECHNOLOGIES AND THEIR IMPACT ON IMPROVING SUPPLY PROCESSES

Smart technologies and new approaches in logistics are key elements that positively impact the acceleration, efficiency, and optimization of supply processes. This chapter describes individual smart technologies and the ways in which they can contribute to the improvement of logistics processes.

3.1 Cyber-Physical Systems and their impact on improving supply processes

Cyber-Physical Systems (CPS) operate based on two-way communication between physical devices—such as conveyors, transport equipment, or warehouse systems—and their digital models. A Digital Twin (DT) is a special type of CPS that accurately represents physical objects or processes in a virtual environment in real time, enabling continuous monitoring and optimization. Thanks to sensor data and advanced planning algorithms, various logistics scenarios and business processes can be evaluated instantly in the digital environment, allowing appropriate actions to be taken directly in real-world operations [6].

Figure illustrates the fundamental concept of Cyber-Physical Systems (CPS), which connect the physical space with the cyber space. The idea behind the figure is that CPS can integrate data from physical devices with software models in real time, resulting in autonomous and dynamically controlled systems with a wide range of real-world applications. CPS have a significant impact on improving supply processes. They provide real-time visibility into inventory by accurately identifying and locating specific items and assessing their current condition. Through the use of digital twins, predictive maintenance becomes possible, allowing companies to anticipate wear and tear on transport and storage systems and avoid unplanned downtimes. Moreover, CPS enable the pre-testing of different warehouse and production layouts in a virtual environment, thereby reducing the time and costs required for physical modifications.

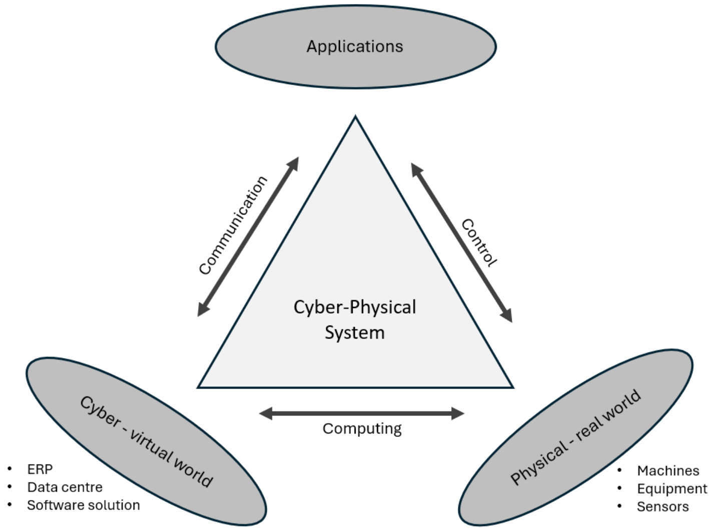


Fig. 1 Basic concept of the CPS (Authors, 2025)

3.2 Intelligent transport units

Intelligent transport units refer to pallets, containers, or crates equipped with various digital elements such as RFID chips, sensors and microprocessors. These components enable autonomous communication, monitoring of the unit's condition or storage environment, and continuous transmission of this information to other devices within the logistics chain. Through built-in computing systems, these transport units can process collected data and become an integral part of cyber-physical systems (CPS). Intelligent transport units are typically equipped with identification chips (RFID/NFC), which allow each unit to carry a unique identifier for fast retrieval and real-time tracking. They also include sensors that evaluate environmental parameters, helping to identify unsuitable storage conditions. Additionally, microprocessors embedded in some units enable local data processing and basic decision-making, such as issuing alerts when set thresholds are exceeded.

An example of an intelligent transport unit is the "iBin" smart bin for small parts developed by Würth Industrie Services. It provides real-time visual information on fill levels, part counts, and reorder conditions.

The use of intelligent transport units (ITUs) significantly improves supply processes by:

- Reducing picking errors through precise identification of components.
- Monitoring storage conditions and alerting when predefined temperature or quantity limits are violated.
- Enhancing warehouse visibility by allowing accurate localization and timely retrieval of units [7].

3.3 RTLS Systems and IoT in the Context of Efficient Supply

RTLS (Real-Time Location Systems) and IoT (Internet of Things) are primarily applied in adaptive logistics to speed up and improve the accuracy of supplying production processes or distribution centers. RTLS provides detailed information about the location of materials and transport equipment, while IoT collects data from sensors and connected devices in real time.
In practice, this means that when a sensor (integrated into a shelf or transport unit) detects a drop in inventory below a critical level, the RTLS immediately identifies the nearest available cart or autonomous robot capable of replenishing the material. Simultaneously, the IoT platform determines where the material should come from and how to optimize the route to avoid unnecessary delays.

The result is a faster response to demand changes and a stable maintenance of the required amount of parts or raw materials in production. RTLS and IoT also increase the transparency of the entire chain: managers can see where each item is located and when it needs to be ordered or moved [8].

3.4 Navigation

Navigation systems play a key role in modern logistics by guiding transport vehicles—such as forklifts, autonomous robots, and tugger trains—efficiently during material picking and transport. Their integration, especially in environments with RTLS technology, brings significant benefits in several areas.

They enable real-time route optimization, reducing transport times by selecting the shortest and least congested paths. This ensures timely delivery of materials and better use of transport capacity. Navigation systems also increase accuracy in order picking by pinpointing item locations and retrieval points, thereby minimizing errors [4].

Moreover, these systems adapt quickly to layout or demand changes, ensuring continuous supply flow even in dynamic environments. As a result, they help reduce inventory levels, shorten lead times, and lower logistics costs through more efficient use of resources.

4. THE BENEFITS OF ADAPTIVE LOGISTICS SYSTEMS FOR SUPPLY

Adaptive logistics systems (ALS) are designed to ensure smooth, fast, and accurate material supply by integrating advanced technologies across the supply chain.
They improve synchronization of orders and deliveries through AGVs, intelligent transport units (IPUs), and real-time ERP/MES integration, allowing continuous route adjustments and optimized delivery. ALS also enables dynamic warehouse inventory management by monitoring capacity in real time, reallocating storage space, and issuing alerts when restocking is needed [9].
Advanced navigation systems within ALS reduce transport times and prevent collisions by planning optimal routes for autonomous vehicles or logistics personnel. Real-time

data on material location and production status allows for efficient task assignment and better use of transport resources, cutting lead times and reducing costs.

Reliability is enhanced by intelligent transport units equipped with sensors and RFID chips that track condition and position. In case of disruptions, the system reroutes materials to avoid delays and minimize production downtime [10].

Finally, technologies like digital twins and smart sensors provide continuous monitoring and predictive supply management, offering full visibility of stock, machines, and logistics operations to maintain a steady and reliable material flow [11, 12].

5. CONCLUSION

Adaptive logistics fundamentally transforms traditional supply practices by promoting greater autonomy, flexibility, and interconnectedness among all elements of the logistics chain. Practical experience shows that the implementation of digital twins, intelligent transport units, RTLS systems, and other adaptive technologies can significantly reduce lead times, minimize errors in order picking, and provide continuous insight into inventory levels, storage capacities, and warehouse utilization.

Through continuous monitoring, real-time localization, and autonomous control of logistics vehicles or transport units, it becomes possible to supply workstations more efficiently, reduce warehousing and logistics costs, respond quickly to increased demand, and eliminate supply disruptions. Ultimately, adaptive logistics contributes to stable and seamless production, lower operating costs, and shorter lead times.

It is therefore evident that companies that implement adaptive logistics principles and technologies in a timely manner will gain a significant competitive advantage in today's industrial and commercial environment.

Acknowledgement

This work was supported by the VEGA Agency under the contract no. 1/0150/24.
This work was supported by the KEGA Agency under the contract no. 017ŽU-4/2025.

References

[1] GREGOR, M. (2015) Industrie 4.0 – Priemysel 4.0. ProIN – Productivity and Innovation. No. 16, č. 2, s. 44-46. ISSN 1339-2271
[2] YANG, W., LI, W., CAO, Y., LUO, Y., HE, L. (2020) An Information Theory Inspired Real-Time Self-Adaptive Scheduling for Production-Logistics Resources: Framework, Principle, and Implementation. Sensors. Available on the internet: https://www.mdpi.com/1424-8220/20/24/7007
[3] GREGOR, M., MEDVECKÝ, Š. (2015) CEIT 2015. CEIT technologické trendy do roku 2030. Štúdia CEIT-Š002-03-2015, Žilina, 2015. 101 s.
[4] GREGOR, M., GREGOR, T., PATKA, J. (2015) Adaptívne logistické systémy (ALS)
[5] GREGOR, M., HALUŠKA, M. (2013) Rekonfigurabilita holonického výrobného systému s podporou agentného prístupu. ProIN – Productivity and Innovation. Roč. 14, č. 6, s. 35–38
[6] THIEDE, S., SULLIVAN, B., DAMGRAVE, R., LUTTERS, E. (2021) Cyber-Physical Systems in Industry 4.0: A Review. Journal of Manufacturing Systems. Available on the internet: https://doi.org/10.1016/j.jmsy.2021.10.009
[7] GREGOR, M., GREGOR, T. (2015) Adaptívne logistické systémy – inteligentné prepravné jednotky.

[8] ASSECO CEIT. (2025) Lokalizácia a monitorovanie. Asseco CEIT. Available on the internet: https://www.asseco-ceit.com/sk/monitorovanie-vyrobnych-systemov/lokalizacia-a-monitorovanie/
[9] KRAJČOVIČ, M., (2020) Digitálne projektovanie výrobných a logistických systémov. Žilina: EDIS. ISBN 978-80-554-1747-9
[10] GREGOR, M., MAGVAŠI, P., (2013) Inteligentné výrobné systémy. Žilinský model Produktivita a inovácie. 14. 31-37.
[11] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research
[12] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

Michaela RYCHTÁRIK[1], Zdenka GYURÁK BABEĽOVÁ[2], Augustín STAREČEK[3]

CORPORATE SOCIAL RESPONSIBILITY AND DIGITAL TRANSFORMATION IN INDUSTRIAL ENTERPRISES

Abstract

The paper explores the intersections between corporate social responsibility and digital transformation in industrial enterprises environment. It analyses the importance of social responsibility as part of corporate strategies. It also highlights the challenges of digitalisation in Slovak enterprises, which face resource and training constraints. The paper highlights the need for strategic linking of activities ensuring growth and prosperity of the enterprise and voluntary activities as a prerequisite for long-term sustainability.

Key words: digital transformation, corporate social responsibility, industrial enterprises,

1. INTRODUCTION

Corporate social responsibility is a hot topic that is not only a subject of intense debate today but is increasingly gaining in importance as we consider the future. It is gradually becoming a standard part of business and its integration in corporate strategies will become more and more frequent. In addition to their core business, businesses play an important role in the lives of their stakeholders, the functioning of their communities and have a major impact on their surroundings and the environment. However, it is also important and necessary for businesses to invest in areas that enable them to improve performance and processes. Digital transformation and technological innovation are now at the forefront of business process improvement. In conjunction with corporate social responsibility, they thus play an important role in achieving sustainability in the management of industrial enterprises.

[1] Ing., Mgr. Michaela Rychtárik, Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, michaela.rychtarik@stuba.sk

[2] doc. Ing. Zdenka Gyurák Babeľová, PhD., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, zdenka.babelova@stuba.sk

[3] Ing. Augustín Stareček, PhD., Ing. Paed. IGIP, Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, augustin.starecek@stuba.sk

2. CORPORATE SOCIAL RESPONSIBILITY IN THE SOCIAL AREA

Numerous definitions of Corporate Social Responsibility (CSR) are characterized by the following common features: accountability to society, responsibility for one's actions (compensating for negative impacts), conducting responsible business, responsibility in a broader sense (including environmental issues) and managing business relationships [13].

CSR can be defined as an individual's commitment to consider the impacts of his or her decisions and actions on society as a whole. Businesses applying CSR consider the interests and needs of stakeholders (suppliers, investors, employees, customers, community, interest groups, etc.) in their operations [7]. CSR represents a commitment for a business to pursue strategies, activities and decisions that are desirable by our society [3]. Businesses adapt their values and behaviours to meet their objectives in line with the expectations and needs of their stakeholders. They should manage their business activities to maximize benefits and minimize negative impacts (Beal, 2014). The main idea of CSR is that businesses are an integral part of society, which they greatly influence through their activities. Corporate responsibility encompasses the economic, legal, ethical, and philanthropic expectations society has with respect to businesses at any given time [4]. A business that defines itself as socially responsible should be active in all three areas (Figure 1).

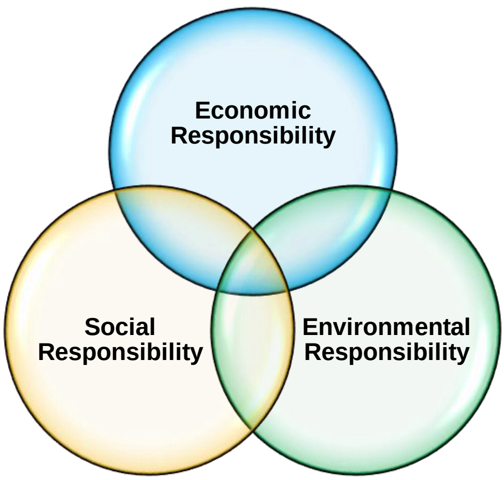


Fig. 1. The three pillars of CSR (own elaboration, 2025)

CSR is also referred to as the triple responsibility of organizations - economic, environmental and social, where the term triple bottom-line is used. The economic area includes transparency, good relations with stakeholders, protection of intellectual property and code of ethics. The environmental area includes green corporate policy, green operations and production, environmental and natural resource protection. The social area encompassed communication with stakeholders, occupational health and safety, adherence to labour standards, non-discrimination, diversity in the workplace and job security [12]. A organisation that defines itself as socially responsible should be proactive in all three areas. Within each of them, it can focus on one type of activity depending on its interests, orientation and the requirements of other stakeholders [1]. Each activity of the organisation affects many actors within its geographical scope. This concerns not only production or services, but also working conditions, innovation, health, environmental protection, promotion of education and respect for human rights [15].

The social area of corporate social responsibility includes respect for human rights, focuses on the care of employees and the working conditions created for employees in the enterprise. The management of the enterprise should aim at continuous improvement of the working environment, training of employees, provision of various benefits, occupational health and safety and anti-discrimination measures. Socially responsible organisations are committed to behaving in accordance with ethical principles - impartiality, active engagement with stakeholders, commitment and transparency. Employees depend on the organisation because work is their main source of income, which is essential for a decent life [14]. The management of an organisation that is committed to the principles of corporate social responsibility has a commitment not only to shareholders, but also to employees, vendors, customers, the community, and to all those who are directly or indirectly affected by its business. Managers of these enterprises recognize the interdependence and interconnectedness of all the interpersonal relationships that enable the enterprise to function [10].

3. DIGITAL TRANSFORMATION AND TECHNICAL INNOVATION

To optimize production processes and improve the operation management of industrial enterprises, the digitalization of industrial enterprises is becoming increasingly important [16]. Digital transformation is also understood as a process in which digital technologies disrupt existing processes, triggering strategic responses from organizations seeking to change their value creation pathways while driving structural changes and organizational barriers that affect the positive and negative outcomes of this process [18]. Digital transformation is organizational change, triggered and shaped by the widespread adoption of digital technologies. The content of this change involves a shift towards flexible organizational structures that are embedded in existing business subsystems that influence how they are managed. This content of change can be viewed from four different perspectives, namely the impact of technology, distributed adaptation, systemic shift, and the holistic perspective of co-evolution. These perspectives address a different contextual scope, but focus on change processes within the organisation. They link organisational change to the nature of digital technologies, which is manifested in particular by their ubiquity and the dynamics they induce. Based on this, digital transformation can be seen as a continuous change that can trigger and shape the changes to emerge [11]. Digital transformation affects many areas of business management and can promote innovation and knowledge flow. However, support from the state is important, as and digital transformation can be influenced mainly by governmental measures and market-oriented aspects [5].

4. DIGITAL TRANSFORMATION AND CORPORATE SOCIAL RESPONSIBILITY OF ORGANISATIONS IN SLOVAKIA

The implementation of new technologies, digital transformation and technological innovation often mentioned in the context of the fourth industrial revolution, bring new challenges and opportunities for improving business processes while emphasizing the responsibility for sustainable development [17]. According to the European Commission, the integration of digital technologies, in all areas, enables companies to improve their outputs and achieve competitiveness. It monitors the digital transformation of businesses through the Digital Intensity Index (DII), which measures the use of different digital technologies in businesses. The index ranks companies according to how much digital technology they use. According to the available surveys, 74% of all EU businesses have reached a baseline level of digital intensity in 2024. It has also shown that there are differences in the level of digital intensity achieved depending on the size of enterprises. While the share was over 98% in large enterprises, it was 73% in small and medium enterprises (SMEs). Compared to large enterprises, which showed a higher share of high and very high intensity, most SMEs reported low or very low levels of digital intensity [9]. However, in addition to differences in enterprise size, there are also demographic disparities. The demographic differences in the level of digital disparity achieved are shown in Figure 2.

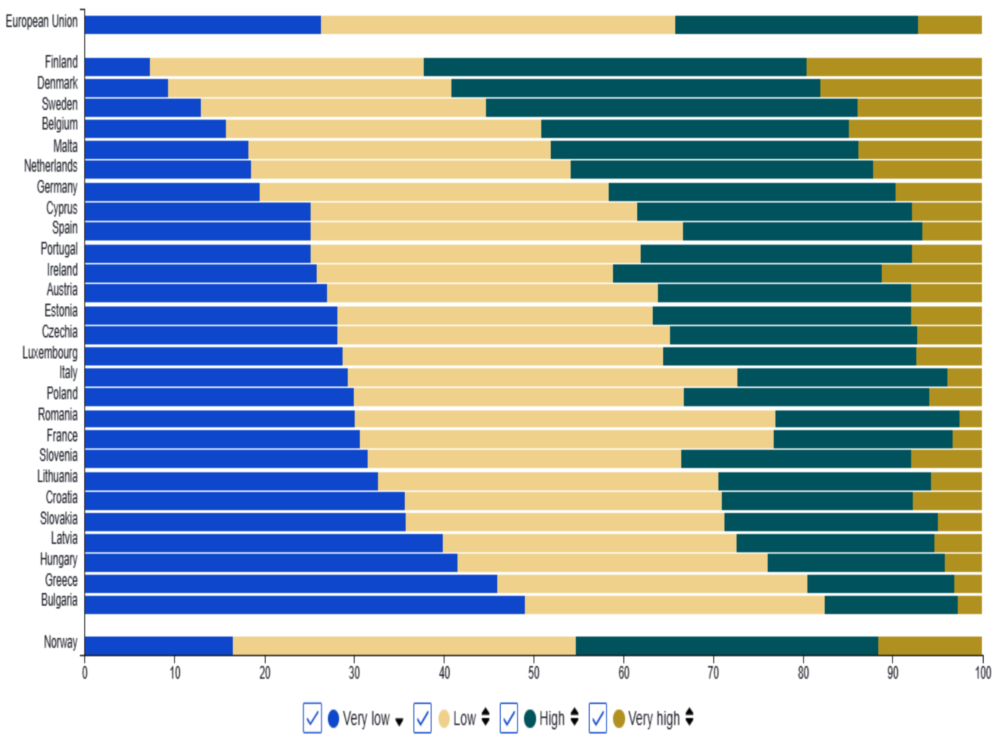


Fig. 2. Differences in the level of digital intensity of businesses between EU countries (Eurostat, 2025)

As can be seen in Figure 2, Slovakia ranks on the 23rd place out of the 27 EU countries ranked. According to the assessment of surveys, the implementation of technologies in the context of Industry 4.0. in Slovakia has been stagnating for a long time. Although the need for digitalisation is growing, Slovak SMEs are lagging in digitalisation and still struggle with a lack of resources and professional skills of their employees. Despite a year-on-year increase of 5% in 2024 (32% fulfilment of the digitalisation strategy) compared to 2023, almost a quarter of industrial enterprises have not yet initiated digitalisation. Enterprises are mainly focusing on digitalizing internal processes that directly affect the production chain, less digitalizing support areas. Within support processes, the areas that are mainly digitised are communication with customers, suppliers or external logistics; maintenance and sales support are perceived as the least important areas [17].

With regard to enterprises investing in measuring sustainability progress, tracking indicators that could declare activities in this area is voluntary and rare. Moreover, a significant limitation for organizations is that they have no way to collect indicators related to sustainability activities digitally and subsequently produce reports on CSR engagement [19]. The European Union declares its support for the implementation of the European Pillar of Social Rights and monitors the Social Survey. It formulates country-specific recommendations to support fiscal and structural reforms, including social policies [8], but does not monitor these activities with regard to the extent of their implementation within industrial enterprises.

5. CONCLUSIONS

Despite the growing importance of digitalisation, many Slovak enterprises are lagging behind their competitors in Europe, facing constraints in terms of both finance and professional capacity. The lack of these resources often hinders their commitment not only to technological innovation but also to socially responsible initiatives. However, given the resounding emphasis on environmental and economic responsibility, it is the social dimension that may be neglected in the context of the principles of corporate social responsibility.

At the same time, if CSR is perceived as a cost item without a strategic anchor, it loses its effectiveness and its benefits for the company and society are limited. Activities carried out without a clearly defined objective and a deeper purpose can lead to inefficient use of organisational resources. For this reason, it is important to systematically link the entrepreneurial activities of enterprises with voluntary initiatives. Only by linking them strategically can enterprises progress towards their long-term sustainability and social benefit.

Acknowledgements

The article is a part of project KEGA No. 010STU-4/2024: *„Creation of a laboratory for the systematic knowledge transfer from the research of personnel aspects of human technology interaction into selected subjects of industrial engineering “.*

References

[1] BAŠISTOVÁ, A., OLEXOVÁ, C. a STANKOVIČ, L. Spoločensky zodpovedné podnikanie s dôrazom na sociálnu oblasť. Trendy v podnikání: vědecký časopis Fakulty ekonomické Západočeské univerzity v Plzni. 2011. Roč. 1, č. 2, s. 5–13. ISSN 1805-0603. Dostupné z: https://www.fek.zcu.cz/tvp/doc/2011-2.pdfphf.euba.sk+1fek.zcu.cz+1

[2] BEAL, B. D. Corporate Social Responsibility: Definition, Core Issues, and Recent Developments. Thousand Oaks: SAGE Publications, Inc., 2014. 95 s. ISBN 978-1-4522-9156-7.

[3] BOWEN, H. R. Social Responsibilities of the Businessman. Iowa City: University of Iowa Press, 2013. 298 s. ISBN 978-1-60938-196-3.

[4] CARROLL, A. B. A Three-Dimensional Conceptual Model of Corporate Performance. Academy of Management Review. 1979. Vol. 4, no. 4, s. 497–505. Dostupné z: https://www.jstor.org/stable/257850jstor.org

[5] CHEN, P., KIM, S. The impact of digital transformation on innovation performance – The mediating role of innovation factors. Heliyon. 2023. Vol. 9, no. 3, e13916. https://doi.org/10.1016/j.heliyon.2023.e13916

[6] ČIRČOVÁ, V., BERESECKÁ, J., BORŠOŠ, P. a ČAPOŠOVÁ, E. Digital transformation of human resource management processes and practices: a study of Slovak enterprises. Entrepreneurship and Sustainability Issues. 2025. Vol. 12, no. 3, s. 315–325. https://doi.org/10.9770/b4647989737

[7] DAVIS, K., BLOMSTROM, R. L. Business and Its Environment. New York: McGraw-Hill, 1966. 403 s. ISBN 978-0-07-015520-6.

[8] EUROSTAT. Sustainable development in the European Union. Luxembourg: Publications Office of the European Union, 2020. ISBN 978-92-76-11724-8. Dostupné z: https://ec.europa.eu/eurostat/statistics-explained/index.php/Sustainable_development_in_the_European_UnionEuropean Commission

[9] EUROSTAT. Digitalisation in Europe – 2025 edition. Luxembourg: Publications Office of the European Union, 2025. Dostupné z: https://ec.europa.eu/eurostat/web/interactive-publications/digitalisation-2025

[10] FERNANDES, P. What Is the Triple Bottom Line? Business.com. 2024. [cit. 23. 5. 2024]. Dostupné z: https://www.business.com/articles/triple-bottom-line-defined/

[11] HANELT, A., BOHNSACK, R., MARZ, D. a MARANTE, C. A Systematic Review of the Literature on Digital Transformation: Insights and Implications for Strategy and Organizational Change. Journal of Management Studies. 2021. Vol. 58, no. 5, s. 1159–1197. https://doi.org/10.1111/joms.12639

[12] JANATKA, F. a kol. Podnikání v globalizovaném světě. Praha: Wolters Kluwer ČR, a.s., 2017. 340 s. ISBN 978-80-7552-754-7.

[13] MOON, J. Corporate Social Responsibility: A Very Short Introduction. Oxford: Oxford University Press, 2014. 160 s. ISBN 978-0-19-967181-6.

[14] PETŘÍKOVÁ, R. Společenská odpovědnost organizací. Ostrava: DTO CZ, 2008. 184 s. ISBN 978-80-02-02099-8.

[15] ROZSA, Z., HOLUBEK, J., VESELÁ, Z. a SOBOLEVA, O. Antecedents and barriers which drive SMEs in relation to corporate social responsibility: Literature review. International Journal of Entrepreneurial Knowledge. 2022. Vol. 10, no. 2, s. 107–122. https://www.ijek.org/index.php/IJEK/article/view/174/146

[16] TIAN, M., CHEN, Y., TIAN, G., HUANG, W. a HU, C. The role of digital transformation practices in the operations improvement in manufacturing firms: A practice-based view. International Journal of Production Economics. 2023. Vol. 262, 108929. https://doi.org/10.1016/j.ijpe.2023.108929

[17] TASR. Prieskum: Podniky zápasia v rámci digitalizácie s nedostatkom zdrojov. Teraz.sk. 2025. [cit. 12. 5. 2025]. Dostupné z: https://www.teraz.sk/spravy/prieskum-podniky-zapasia-v-ramci-digi/853694-clanok.html

[18] VIAL, G. Understanding digital transformation: A review and a research agenda. The Journal of Strategic Information Systems. 2019. Vol. 28, no. 2, p. 118–144. https://doi.org/10.1016/j.jsis.2019.01.003

[19] VRABCOVÁ, P., URBANCOVÁ, H. a HUDÁKOVÁ, M. Strategic Trends of Organizations in the Context of New Perspectives of Sustainable Competitiveness. Journal of Competitiveness. 2022. Vol. 14, no. 2, s. 174–193. https://doi.org/10.7441/joc.2022.02.10

Veronika SEDLÁKOVÁ[1], Fabián ČIKOVSKÝ[2], Dominik HAKULIN[3]

STEM CELL VIABILITY AND GROWTH IN ELECTROMAGNETIC ENVIRONMENTS

Abstract

Magnetic fields represent a promising biophysical factor capable of influencing stem cell behavior. This article reviews current studies on the effects of static and low-frequency magnetic fields on the viability, proliferation, and differentiation of stem cells. The findings suggest that the biological response depends on field parameters such as intensity and exposure duration. Understanding these interactions may help optimize conditions for future applications in regenerative medicine and tissue engineering.

Key words: magnetic field, stem cell, proliferation, viability

1. INTRODUCTION

Magnetic fields are an inseparable part of our daily environment. With increasing exposure to various electromagnetic sources due to technological development, the question of their biological impact remains open. Among the many studied effects, the influence of magnetic fields on stem cells, particularly their viability and proliferation, has become a field of growing interest [1,2].

Stem cells play an essential role in both embryonic development and adult tissue maintenance. During early stages of life, they ensure proper growth and organ formation by continuously dividing and giving rise to specialized cells. In adulthood, they help maintain tissue balance by replacing damaged or aging cells and supporting regeneration processes. One of their key characteristics is asymmetric division, where one daughter cell retains stem cell properties while the other differentiates. Mesenchymal stem cells are of particular interest due to their potential to differentiate into various cell types and their ability to modulate immune responses [3,4].

[1] Bc., Ing. Veronika Sedláková, Technical University of Košice, Faculty of Mechanical Engineering, Letná 1/9, 042 00 Košice, veronika.sedlakova@tuke.sk

[2] Fabián Čikovský, Technical University of Košice, Faculty of Mechanical Engineering, Letná 1/9, 042 00 Košice, fabian.cikovsky@student.tuke.sk

[3] Dominik Hakulin, Datacomp s.r.o, Moldavská cesta 32, 040 11 Košice, Slovakia, hakulin.dominik@datacomp.sk

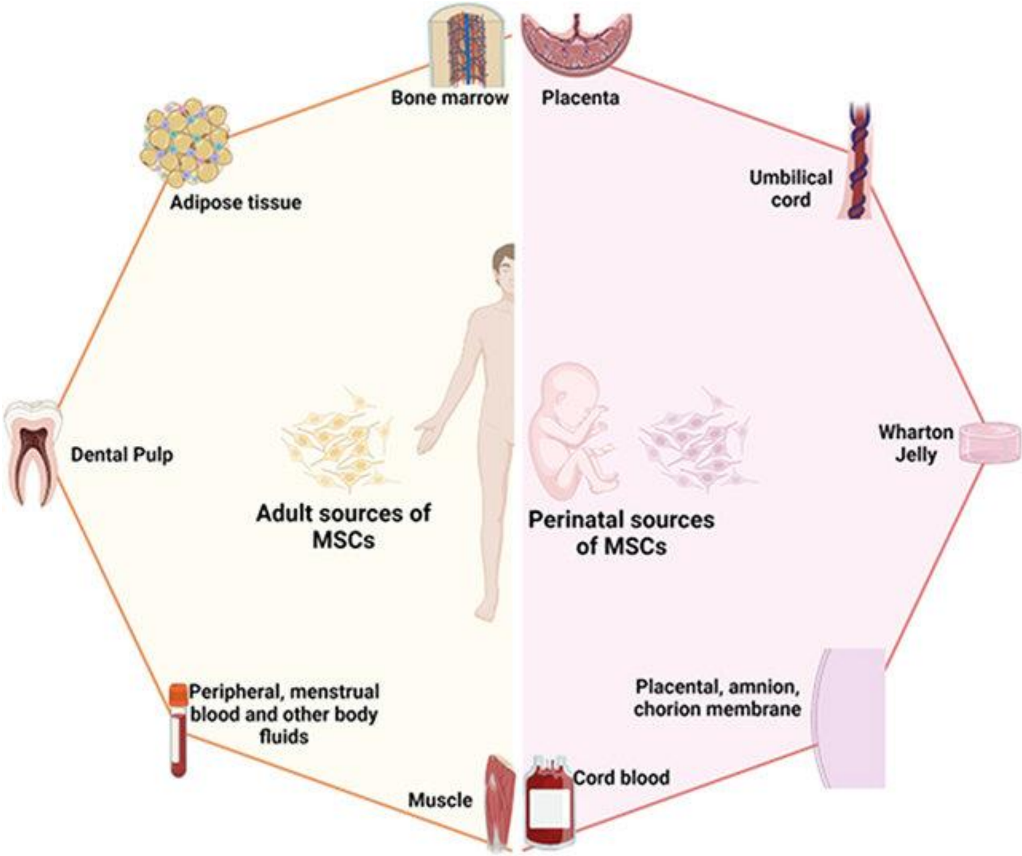


Fig. 1. Sources of adult and perinatal MSCs [4].

Recent advances in biophysical research have highlighted the role of physical stimuli such as light, sound and electromagnetic fields in modulating cellular behavior. Among these, magnetic fields stand out for their non-invasive nature and ability to penetrate tissues without direct contact or heat production. This makes them a promising tool for influencing stem cell activity in a controlled and targeted manner [5].

Various types of magnetic fields, including static magnetic fields (SMFs) and extremely low frequency electromagnetic fields (ELF EMFs), have been investigated for their potential to affect cell physiology. The response of stem cells to magnetic stimulation is complex and appears to depend on multiple factors including the field's strength, frequency, exposure duration and the biological context of the cells. In particular, moderate intensity static fields have shown potential in enhancing proliferation and guiding differentiation, especially toward osteogenic and chondrogenic lineages [6,7].

The increasing interest in this area stems from its potential applications in regenerative medicine where magnetic field exposure could be used to improve the efficiency of stem cell based therapies, support tissue repair or reduce dependence on biochemical factors. Despite promising early results, the mechanisms through which magnetic fields exert their effects on stem cells remain incompletely understood and continue to be a subject of active investigation [8].

2. METHODS AND METHODOLOGY

This section includes a comprehensive review and synthesis of relevant peer-reviewed scientific studies that investigate the effects of different types, intensities, and durations of magnetic field exposure on stem cells. The analysis focuses on the impact on cell viability, proliferation, and differentiation pathways.

Tab. 1. Types of stem cells and their response to magnetic fields

Cell type	**Sensitivity to SMF**	**Ideal intensity**	**Main effects**
MSC	High	10–15 mT	Higher proliferation and osteogenesis
ASC	High	10–15 mT	Higher proliferation, lower adipogenesis at 0.5 T
BM-MSC	High	10–15 mT	Higher proliferation and mineralization
UB-MSC	Medium high	10–15 mT	Higher proliferation and mineralization
PDLSC	Very high	15 mT	Higher osteogenesis and cementogenesis
DPSC	High	10–15 mT	Higher proliferation and osteogenesis
NSC	Unclear	>15 mT + SPIO	Increased neuronal markers

3. RESULTS AND DISCUSSION

The effects of magnetic fields on stem cells depend on various factors, including the intensity of the field, duration of exposure and the specific cell type. This section provides an overview of the reviewed studies, focusing on different types of magnetic stimulation and their biological effects. Special attention is given to how these fields influence stem cell viability, proliferation and differentiation, based on findings from studies using both static and low-frequency electromagnetic fields.

3.1 Summary of Reviewed Studies

The most widely studied magnetic field type was the static magnetic field (SMF), typically generated using neodymium-iron-boron (NdFeB) permanent magnets. None of the studies reported cytotoxic effects of SMF. Intensities up to 15 mT had either neutral or stimulatory effects on stem cells. However, higher intensities around 0.5 T exhibited mild inhibitory effects on viability when applied for over 7 days [6,7].

In terms of proliferation, SMF intensities in the range of 10–15 mT demonstrated the most consistent positive effects. Higher intensities (≥ 0.5 T) tended to be inhibitory. Most studies focused on osteogenic differentiation, which was generally enhanced by SMF exposure [5,8].

The second major type, ELF electromagnetic fields (ELF-EMF), was typically generated using solenoid coils. Again, no cytotoxicity was observed, and viability was often slightly increased even with prolonged exposure (> 7 days). However, the effects on proliferation were generally weaker compared to SMF. ELF-EMFs primarily supported differentiation, especially osteogenesis and in some cases, chondrogenesis, such as in the study by Zerillo et al. (2024) involving adipose-derived stem cells [9].

incorporating biocompatible nanomaterials such as superparamagnetic iron oxide nanoparticles (SPIO), magnetic hydrogels, or graphene oxide did not observe decreased viability. These materials, in combination with magnetic fields, had a neutral effect on proliferation but often altered the direction of differentiation. For instance, He et al. (2021) reported enhanced osteogenic differentiation with graphene oxide [11].

3.2 Biological Effects by Magnetic Field Intensity

Low Intensities (< 5 mT): Slight increase in proliferation, although often not statistically significant. Viability was preserved with no cytotoxic signs. Weak or no activation of osteogenic differentiation. Supporting studies: Javani Jouni et al. (2013); Kaya et al. (2021) [10,12].

Medium Intensities (5–100 mT): Strongest and most consistent stimulation of proliferation across various stem cell types (PDLSC, MSC, DPSC), particularly around 15 mT. Significantly increased extracellular matrix mineralization and osteogenic/cementoblastic differentiation. Ideal for bone and dental tissue engineering. Supporting studies: Kim et al. (2017); Lew et al. (2018); Chang et al. (2020) [6,7,8].

High Intensities (> 100 mT): Viability remained intact, but prolonged exposure may lead to cytostatic effects, reducing proliferation. Differentiation tended to shift toward osteogenesis while adipogenesis was inhibited. This effect is potentially beneficial in treating conditions such as osteoporosis. Supporting studies: Wang et al. (2016); Guo et al. (2023) [3,13].

4. CONCLUSION

Magnetic fields can modulate stem cell behavior depending on their strength, exposure duration and the type of cell. The most notable effects include improved proliferation and direction of differentiation toward osteogenic and chondrogenic lineages, especially under moderate field intensities around 10 to 15 mT. While higher intensities may reduce proliferation, they can still promote specific differentiation pathways.

These interactions highlight the potential of magnetic environments to support stem cell research and tissue engineering. By fine-tuning field parameters, it may be possible to develop more effective strategies for enhancing regeneration without relying solely on chemical factors. However, further research is necessary to fully understand these mechanisms and ensure safe implementation in biomedical applications.

Acknowledgements

The work has been supported by research grants Agency-project VEGA 1/0387/22 – "Development and testing of systems for controlled stimulation of cell growth in a bioreactor environment using computer vision". This work was supported by the project APVV-20-0068 – "Development of new bioresorbable alloys for intracellular implants". This publication is the result of the project implementation CEMBAM - Center for Medical Bioadditive Research and Production, ITMS2014+: 313011V358 supported by the Operational Programme Integrated Infrastructure funded by the European Regional Development Fund. References.

References

[1] SADRI, MARYAM, et al. Static magnetic field effect on cell alignment, growth, and differentiation in human cord-derived mesenchymal stem cells. *Cellular and Molecular Bioengineering*, 2017, 10.3: 249-262.

[2] MUELLER, CORNELIA EMIKA, et al. Influence of static magnetic fields on human myoblast/mesenchymal stem cell co-cultures. *Molecular medicine reports*, 2018, 17.3: 3813-3820.

[3] MENG, JIE, et al. Super-paramagnetic responsive nanofibrous scaffolds under static magnetic field enhance osteogenesis for bone repair in vivo. *Scientific reports*, 2013, 3.1: 2655.

[4] D'SOUZA, RYAN S., et al. Evidence-based clinical practice guidelines on regenerative medicine treatment for chronic pain: a consensus report from a multispecialty working group. *Journal of pain research*, 2024, 2951-3001.

[5] LEW, WEI-ZHEN, et al. Static magnetic fields enhance dental pulp stem cell proliferation by activating the p38 mitogen-activated protein kinase pathway as its putative mechanism. *Journal of Tissue Engineering and Regenerative Medicine*, 2018, 12.1: 19-29.

[6] CHANG, CHING-YI, et al. Static magnetic field-enhanced osteogenic differentiation of human umbilical cord-derived mesenchymal stem cells via matrix vesicle secretion. *International Journal of Radiation Biology*, 2020, 96.9: 1207-1217.

[7] KIM, EUN-CHEOL, et al. Static magnetic fields promote osteoblastic/cementoblastic differentiation in osteoblasts, cementoblasts, and periodontal ligament cells. *Journal of periodontal & implant science*, 2017, 47.5: 273-291.

[8] GUO, ZHAOYUAN, et al. Static magnetic fields promote generation of muscle lineage cells from pluripotent stem cells and myoblasts. *Stem Cell Reviews and Reports*, 2023, 19.5: 1402-1414.

[9] ZERILLO, LUCREZIA, et al. Extremely low frequency–electromagnetic fields promote chondrogenic differentiation of adipose-derived mesenchymal stem cells through a conventional genetic program. *Scientific Reports*, 2024, 14.1: 10182.

[10] KAYA, M. O. L. O.; EMEL, O. R. D. U. Effect of Moderate Static Magnetic Field on Human Bone Marrow Mesenchymal Stem Cells: a Preliminary Study for Regenerative Medicine. *Trakya University Journal of Natural Sciences*, 2021.

[11] HE, Yi, et al. Effect of magnetic graphene oxide on cellular behaviors and osteogenesis under a moderate static magnetic field. *Nanomedicine: Nanotechnology, Biology and Medicine*, 2021, 37: 102435.

[12] JAVANI JOUNI, FATEMEH; ABDOLMALEKI, PARVIZ; MOVAHEDIN, MANSOUREH. Investigation on the effect of static magnetic field up to 15 mT on the viability and proliferation rate of rat bone marrow stem cells. *In Vitro Cellular & Developmental Biology-Animal*, 2013, 49: 212-219.

[13] WANG, JIAN, et al. Externally applied static magnetic field enhances cardiac retention and functional benefit of magnetically iron-labeled adipose-derived stem cells in infarcted hearts. *Stem cells translational medicine*, 2016, 5.10: 1380-1393.

Augustin STAREČEK[1], Natália VRAŇAKOVÁ[2],
Zdenka GYURÁK BABEĽOVÁ[3]

THE APPLICATION OF EDUCATIONAL ROBOTS IN EDUCATION OF INDUSTRIAL ENGINEERS

Abstract

We focused on the selected model of educational robots and the possibilities of their use in education in the presented article. The main aim of the article is to describe the implementation of an innovative training set of educational robots into the process of education of industrial engineers. Innovated educational process helps university students develop skills for effective and sustainable organizational management. The results can help universities and other institutions improve the quality of education.

Key words: education, educational robots, industrial engineering, robotics.

1. INTRODUCTION

The actual need to improve the quality of the educational process of future industrial engineers at universities requires taking into account current technological trends. The digitalization, automation in the form of robotization or robotization, as well as its other forms, resonate in the current industrial environment. Due to the ongoing material, technological changes, the need to study the mutual interaction of people with technologies with an emphasis on the human factor is increasing, which will help to better understand various aspects of the introduction of changes and the conditions for employees to adapt to new technologies. Education of future industrial engineers and managers should include new scientific and technological knowledge.

2. LEVERAGING ROBOTS IN EDUCATION

Learning and development are defined as the processes of ensuring that an organization has educated, skilled and engaged employees. The process facilitates

[1] Ing. Augustín Stareček, PhD., Ing. Paed. IGIP, Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, augustin.starecek@stuba.sk

[2] Ing. Natália Vraňaková, PhD., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, natalia.vranakova@stuba.sk

[3] doc. Ing. Zdenka Gyurák Babeľová, PhD., Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Jána Bottu č. 2781/25, 917 24 Trnava, Slovakia, zdenka.babelova@stuba.sk

individuals and teams to acquire required knowledge, skills and abilities through their own experiences, training programs and methods, coaching and other techniques [1]. Education is a complex process of acquiring, developing and transmitting knowledge, skills, values, habits and attitudes through various forms and methods of learning [2]. Education includes formal education, which usually takes place in schools and educational institutions, as well as informal education, which can take place in the workplace or in everyday life [3]. The article [4] defines education as a critical process that involves not only acquiring knowledge and skills but also motivating students to apply the acquired knowledge and skills effectively. This approach is vital to ensuring the sustainability of education, especially in the context of business value creation, where motivated and well-educated individuals can significantly contribute to sustainable practices and societal growth. According to authors [5] education is understood as a systematic process of developing the skills, knowledge and competences of individuals, preparing them to function effectively in various fields, including entrepreneurship in the agriculture, food and nutrition sector. This process is essential for providing the necessary tools and expertise that support the innovative potential that can be used in business practice.

One way to bring education closer to business practice is using educational robots. These are used in specialized laboratories to simulate industrial processes, allowing students to gain practical experience with robotics and digital engineering [6]. In addition to teaching programming and simulations, they help in the design of logistics systems, where they enable the testing of small physical models and methodologies in the field of industrial logistics [7]. The low cost and compact dimensions of educational robots make them an affordable alternative to large industrial robots, expanding educational opportunities in the field of automation and digitalization [8]. Educational robots provide an opportunity for learning and interaction with new technologies in acceptable conditions. Educational robotics, or robotics in education, is terminology widely associated with the use of robotics as an educational tool in teaching. This approach is closely linked to the concept of gamification in education. It is an effort to introduce playful elements into teaching that are motivating and make the learning process more fun [9]. The popularity and interest in robotics have skyrocketed in the past few years, especially in the educational community. Robotics technology, once only accessible to experts and scientists, is increasingly accessible to teachers and students [10].

3. POSSIBILITIES OF USING EDUCATIONAL ROBOTS IN THE EDUCATIONAL PROCESS

The third part of the presented article is devoted to the possibilities of using the selected model of educational robots to improve the quality of education of subjects in industrial engineering. Implementing an active and practical approach to education based on participation and team solving of problems that industrial engineers and managers encounter in their work leads to an improvement of the educational process. Educational robots were used in teaching in the form of robotic kits to enable targeted preparation of students and development of their complex skills necessary for sustainable management of the performance of employees and organizations. Operating educational robots is simple and interactive and has many advantages over theoretical education. The possibilities of using educational robots are extensive and they are used in schools and outside them. The slow pace of adoption of robotics in the past is partly explained by the high cost of the kits, coupled with different priorities for schools in accessing technology. Recently, the cost of kits has decreased, while the equipment and availability of supporting hardware and software have increased. We can conclude that robots are more accessible than in the past [10].

The robotic set included two robots, the Wlkata Mirobot Professional Kit 6-axis robotic arm and one conveyor belt Conveyor belt Set Robotic arms. In Figure 1, we can see the educational robots and the conveyor belt that cooperate and are intended for the education of future industrial engineers.

Fig. 1. Educational equipment Robotic arms and Conveyor belt (own elaboration, 2024)

The listed devices consist of several components, which together with technological equipment create a unique device that can be used not only for programming, but also for simulating the production process. The six-axis robotic devices include the following components robotic arm, Power supply and high-speed USB cable and IDC cable, holding pen, Micro servo gripper module, Pneumatic kit (including pneumatic box, suction cup, two-finger gripper, three-finger soft gripper), Multifunction box, Mirobot calibration board and Mecha sticker, Manual and Bluetooth wireless controller. For the purposes of analyzing the educational tool, Table 1 was created, which contains the basic parameters of the educational device.

Tab. 1. Robotic devices parameters – Detail [11]

Product Name:	**WLKATA Mirobot**	
Robotic Arm Basic Parameter	Number of axes	6+1
	Standard payload	250g
	Maximum payload	400g
	Workspace	315mm
	Base dimensions	Diameter 160mm
	Position accuracy	0.2mm
	Type of the six joints	High accuracy stepping motor + reducer
Robotic Arm Axis Motion Parameter (160g)	1-axis	-110° ~ +160° maximum speed 85°/s
	2-axis	-35° ~ +70° maximum speed 60°/s
	3-axis	-120° ~ +60° maximum speed 65°/s
	4-axis	-180° ~ +180° maximum speed 200°/s
	5-axis	-200° ~ +30° maximum speed 200°/s

Used 6-axis robotic arm was designed for educational purposes in the field of robotics and automation. This arm supports simulations in ROS (Robot Operating System) and MATLAB, making it ideal for teaching and research in technical fields of study. In Figure 2 we can see the complete set with all its components described above.

Fig. 2. Educational equipment Wlkata Mirobot [11]

The main parameters include [11]: Robotic arm is a compact robotic manipulator offering flexibility and mobility comparable to that of industrial robots. It supports a variety of control and programming platforms, including ROS, MATLAB, and its proprietary software, facilitating intuitive simulation and educational use. Operating at a voltage of 12 V, it is well-suited for integration into educational environments. Its desktop-friendly dimensions allow for seamless implementation in both teaching and research settings.

Subsequently, the possibilities of using educational robots were identified to ensure the improvement of the quality of education of industrial engineers. After completing the subjects Fundamentals of Production Management and Enterprise Logistics, the student will gain advanced knowledge of production management in an industrial enterprise, the creation of a production strategy, technology planning and production preparation. They will also master the processes of managing the main production, innovation and efficiency of the production units. In the field of enterprise logistics, it will be focused on supply, production logistics, distribution and key logistics trends [12]. The expected benefits and opportunities include [12]:

- linking the creation of a production strategy with robotization, effective deployment of robotic workplaces,
- comparison of human and robotized production,
- clarification of the advantages and disadvantages of robotization in various types of production
- increasing the attractiveness of the study of Industrial Management thanks to work with modern technologies.

Another identified subject is Production Management. It focuses on managing production processes in a company, including planning, organising, controlling and optimising resources. The goal is to increase productivity and quality, minimise costs and meet schedules. It uses methods such as production planning, inventory management and process improvement, thereby strengthening the competitiveness of the company. The training set simulates production processes, identifies waste and creates visual standards. The inclusion of robots in the teaching of Production Management allows students to better understand the relationship between manual and automated work in one production process [12]. Industrial engineers also need soft skills and knowledge in the field of human resource management and personnel management. These are two more subjects from which the student will gain knowledge in human resource management with a focus on change management, performance measurement, career management, talent management and modern methods of employee development. They will master the creation of performance evaluation systems, career plans, personnel processes such as planning, recruitment, selection and adaptation. Among the most important advantages and opportunities of implementation in these subjects were listed [12]:

- modernizing approaches in human resources and personnel management,
- adapting recruitment and selection of employees to digitalization and automation based on experience with the educational set,
- taking digitalization and automation into account in the adaptation and assessment of employees,
- emphasizing the importance of education and digital skills in talent management and career development.

Technological specifications indicate that the used robotic arm, together with the conveyor belt, represents an effective tool for teaching and research in the field of human-technology interaction.

4. CONCLUSIONS

The conducted analysis of the theoretical foundations as well as the functionalities of the used robotic arm and conveyor belt demonstrated that by their active use it is possible to integrate game learning into education and thus increase the quality of the pedagogical process. The used robotic arms and conveyor belt not only enabled the simulation of real industrial scenarios but also provided students with practical experience with technologies and automation. The introduction of educational robots into the educational process contributed to a better understanding of human-robot cooperation, supported machine learning and adaptability, and demonstrated the importance of automation and digital transformation in a modern industrial environment. The results indicated that modern and interactive educational methods are key to developing the necessary skills and competencies for jobs in industry. For future research and practice, it is important to continue developing and implementing similar educational tools and technologies that support the integration of theoretical and practical aspects of education while responding to the ever-changing needs of the labour market. The authors of the article will also conduct a series of experiments, testing a test and control group of students.

Acknowledgements

The article is a part of project KEGA No. 010STU-4/2024: *„Creation of a laboratory for the systematic knowledge transfer from the research of personnel aspects of human technology interaction into selected subjects of industrial engineering “.*

References

[1] ARMSTRONG, M. and TAYLOR, S. Řízení lidských zdrojů: Moderní pojetí a postupy – 13. vydání. Praha: Grada Publishing, a.s., 2015. ISBN 978-80-247-5258-7.

[2] SEEMANN, P., ŠTOFKOVÁ, Z., POLIAKOVÁ, A., BIŇASOVÁ, V. and LOUČANOVÁ, E. Coaching Approach as a Sustainable Means of Improving the Skills of Management Students. *Administrative Sciences*. 2024. Vol. 14, no. 6, p. 114. https://doi.org/10.3390/admsci14060114

[3] DARLING-HAMMOND, L., FLOOK, L., COOK-HARVEY, C., BARRON, B. and OSHER, D. Implications for educational practice of the science of learning and development. *Applied Developmental Science*. 2 April 2020. Vol. 24, no. 2, p. 97–140. https://doi.org/10.1080/10888691.2018.1537791

[4] KUCHARČÍKOVÁ, A., MIČIAK, M., MALICHOVÁ, E., ĎURIŠOVÁ, M. and TOKARČÍKOVÁ, E. The Motivation of Students at Universities as a Prerequisite of the Education's Sustainability within the Business Value Generation Context. *Sustainability*. 10 October 2019. Vol. 11, no. 20, p. 5577. https://doi.org/10.3390/su11205577

[5] SMOLOVÁ, H., KUBOVÁ, P. and URBANCOVÁ, H. Success Factors for Start-ups Related to Agriculture, Food and Nutrition and Their Relevance to Education. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*. 28 June 2018. Vol. 66, no. 3, p. 791–801. https://doi.org/10.11118/actaun201866030791

[6] PEKARČÍKOVÁ, M., TREBUŇA, P., KLIMENT, M. and KRONOVÁ, J. Wlkata Educational Robots in the Specialised Laboratory. *Trends and Innovative Approaches in Business Processes*. 2024. Vol. 27, no. 1, p. 37–41.

[7] KOVALČÍK, J., STRAKA, M. and TROJANOWSKA, J. Utilize Educational Robots to Design Logistic Systems. *Applied Sciences*. 2024. Vol. 14, no. 13, p. 5664. https://doi.org/10.3390/app14135664

[8] PEKARČÍKOVÁ, M., TREBUŇA, P., KLIMENT, M. and DIC, M. Wlkata educational robots used in simulation in laboratory conditions. *Acta Simulatio*. 2023. Vol. 9, no. 3, p. 33–37. https://doi.org/10.22306/asim.v9i3.101

[9] JURÍK, P. Rozvíjajúce sa trendy a budúcnosť e-learningu. *Economics and Informatics*. Online. 23 November 2016. Vol. 14, no. 2. [Accessed 20 March 2025]. Available from: https://ei.fhi.sk/index.php/EAI/article/view/66

[10] SZIVÓSOVÁ, M. Vývoj a modely edukatívnych robotov. *Economics and Informatics*. Online. 2 June 2021. Vol. 19, no. 1. [Accessed 25 March 2025]. Available from: https://ei.fhi.sk/index.php/EAI/article/view/216

[11] WLKATA. *We Make Embodied AI Robotics Solution For Education*. 2024. [Accessed 15 March 2025]. Available from: https://www.wlkata.com/

[12] VRAŇAKOVÁ, N., MESÁROŠOVÁ, J. and JURÍK, L. Innovation of the teaching process focused on exploring the interactions of people with technologies. In: *EDULEARN24 Proceedings*. Online. Palma, Spain: IATED Academy, 2024. p. 10411–10419. [Accessed 20 March 2025]. ISBN 978-84-09-62938-1. https://doi.org/10.21125/edulearn.2024.2559

Janka SZABOVÁ[1], Miroslav DADO[2], Jozef SALVA[3]

REVIEW OF METHODS FOR MEASURING BRAKE WEAR PARTICULATE EMISSIONS

Abstract

Brake wear particulate matter has emerged as a significant contributor to non-exhaust vehicular emissions, with implications for air quality and public health. This review consolidates current methodologies for measuring brake wear particle emissions, encompassing laboratory-based techniques and on-vehicle sampling systems. We examine the principles, advantages, limitations, and applications of various measurement methods, providing a critical assessment of their effectiveness in capturing the complexity of brake wear emissions.

Key words: brake wear aerosol, non-exhaust emissions, measurement, concentration

1. INTRODUCTION

The proliferation of brake wear particulate emissions has emerged as a critical issue in the landscape of vehicular pollution. Unlike tailpipe emissions, which are steadily decreasing due to stringent regulatory frameworks and widespread adoption of cleaner fuels and engine technologies, non-exhaust emissions such as brake, tire, and road wear are gaining relative prominence. Among these, brake particulate emissions constitute a substantial fraction of airborne PM2.5 and PM10 concentrations in urban environments, posing serious health and environmental concerns [1].
Brake wear particulate matter (BWPM) is generated during frictional contact between the brake pad and rotor, resulting in thermal and mechanical degradation of pad and disc materials. This process emits a complex mixture of metallic particles (e.g., Fe, Cu, Zn), organic compounds, and carbonaceous fragments. These particles vary widely in morphology, size (from ultrafine to coarse), and composition, influencing their atmospheric behaviour and health effects.
Accurate quantification and characterization of BWPM are essential for policy development, health risk assessments, and the design of cleaner braking systems. However, the measurement of brake particles is fraught with technical challenges due to their transient nature, sampling losses, and the lack of unified protocols. This has led

[1] Janka Szabová, Ing., Technical University in Zvolen, Faculty of Technology, Študentská 26, 960 01 Zvolen, xszabova@is.tuzvo.sk
[2] Miroslav Dado, doc. Ing. PhD, Technical University in Zvolen, Faculty of Technology, Študentská 26, 960 01 Zvolen, miroslav.dado@tuzvo.sk
[3] Jozef Slava, Ing. PhD, Technical University in Zvolen, Faculty of Ecology and Environmental Sciences, T. G. Masaryka 24, 960 01 Zvolen, xsalvaj@is.tuzvo.sk

to significant variability in reported emission factors across different studies, hindering the formulation of consistent mitigation strategies.
The objective of this review is to present a comprehensive analysis of the methodologies employed in measuring brake particulate emissions. We examine both established and emerging techniques, dissect their underlying principles, highlight the strengths and limitations of each method, and evaluate their alignment with regulatory and industrial requirements.

2. LABORATORY BASED MEASUREMENT METHODS

2.1 Brake dynamometers

Brake dynamometers are among the most widely used laboratory platforms for simulating braking events under controlled conditions. These devices are designed to replicate real-world braking scenarios while allowing the measurement of brake wear particle generation. Typically, a dynamometer system includes a rotating disc or drum driven by an electric motor, against which a brake calliper and pad assembly is actuated according to a pre-defined braking cycle. There are several types of brake dynamometers (Fig. 1):

- inertia dynamometers [2-5],
- chassis dynamometers [6-8].

Brake dynamometers provide unparalleled control over test parameters such as temperature, pressure, rotor speed, braking torque, and contact pressure. These conditions can be fine-tuned to replicate specific driving cycles (e.g., WLTP-Brake) and vehicle load scenarios.
The major advantages include:

- repeatability and reproducibility of test conditions,
- isolation of variables like material composition or cooling airflow,
- ease of integrating particle measurement instruments.

Despite careful simulation, dynamometers cannot fully replicate real-world braking behaviour, including driver variability, road grade, and weather. Particles may behave differently in the confined space of the test rig compared to open environments.

Fig. 1. Brake dynamometers [3], [7]

2.2 Pin-on-Disc Apparatus

The pin-on-disc apparatus (Fig. 2) involves the contact of a pin (representing the brake pad) with a rotating disc (representing the brake rotor), simulating the wear process. This method allows for detailed analysis of wear mechanisms and particle generation but may not accurately replicate the complex dynamics of actual braking systems.

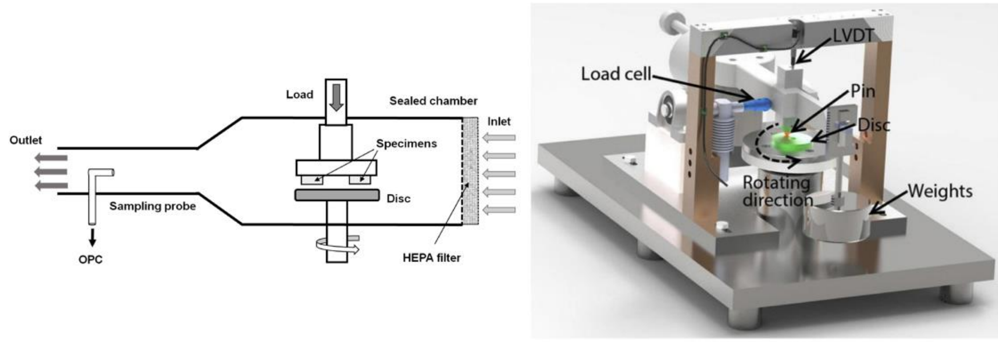


Fig. 2. Pin-on-Disc Tribometer [9], [10]

The major advantages include:

- requires only small samples of pad and disc material, making it cost-effective and useful for early-stage testing or material screening,
- load, speed, temperature, and atmosphere can be precisely controlled, allowing for reproducible experiments,
- enclosed or partially enclosed designs facilitate collection and characterization (e.g., size, morphology, composition) of airborne wear particles,
- less expensive and simpler to operate than full-scale dynamometer.

The main shortcomings include:

- the simplified contact geometry (e.g., point or line contact) does not fully replicate the complex real-world contact and pressure distribution of full brake systems,
- the system may not accurately reproduce the high thermal loads experienced in real braking scenarios, affecting wear and oxidation behaviour,
- results may not directly translate to full-scale brake systems due to differences in size, mass, and dynamic interactions.

3. ON-VEHICLE MEASUREMENT SYSTEMS

Laboratory conditions often fail to capture the complexity of real-world driving, where factors such as sudden braking, varying speeds, and different road textures can significantly influence brake wear and particle emissions [11]. On-vehicle measurement systems are used to quantify and characterize brake wear particles generated during real-world driving.

3.1 Open sampling system

The open sampling system is the simplest design for real driving particle measurements. In an open sampling setup, air sampling inlets are positioned close to the brake assembly, typically near the brake calliper or wheel well, on an actual test vehicle. These inlets are connected to sampling lines that transport the collected air to particle measurement instruments (Fig. 3). A primary limitation of on-vehicle open sampling systems is the potential intrusion of non-brake-related particulate matter, such as road dust, tire wear particles, and ambient air pollutants, into the sampling inlet, which complicates the accurate identification and quantification of brake wear particles.

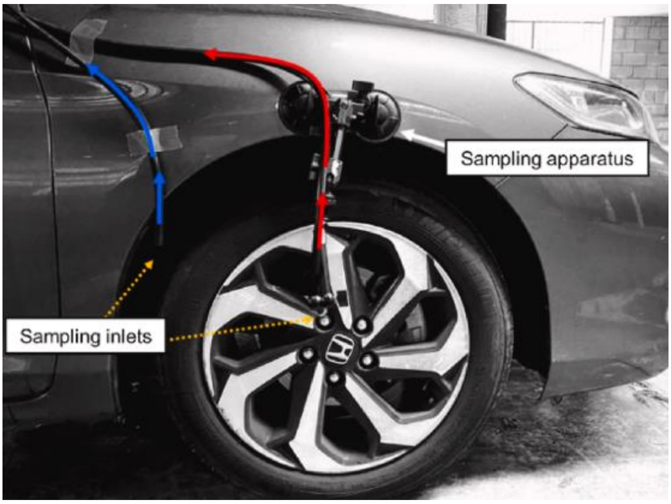


Fig. 3. Sampling inlet in open system [12]

3.2 Semi-closed sampling system

A semi-closed sampling system incorporates a partially enclosed sampling chamber that surrounds the sampling inlet. This design reduces the direct exposure of the inlet to the surrounding environment, such as road dust and ambient air, which is a key challenge in open sampling systems. Compared with the open sampling system, the semi-closed sampling system could reduce the effects of particle distribution inhomogeneity, resuspension of particles, and tire abrasion, but these effects still exist, which means the quantitative results still get large uncertainty [13].

3.3 Closed sampling system

The main principle of the closed system design is to seal the brake system from the environment. Several approaches were identified for the design of the brake enclosure, as illustrated schematically in Fig. 4. These design approaches are:

- To seal the front face of the wheel using the wheel itself as the rotating outer enclosure and construct a static inner enclosure with the interface between it and the wheel rim.

- To construct a static enclosure around the brake, with the interface between the static enclosure and the rotating wheel hub.
- To attach the outer part of the enclosure to the wheel, with which it rotates, and construct a static inner enclosure, with the interface between the static inner and rotating outer enclosure elements [14].

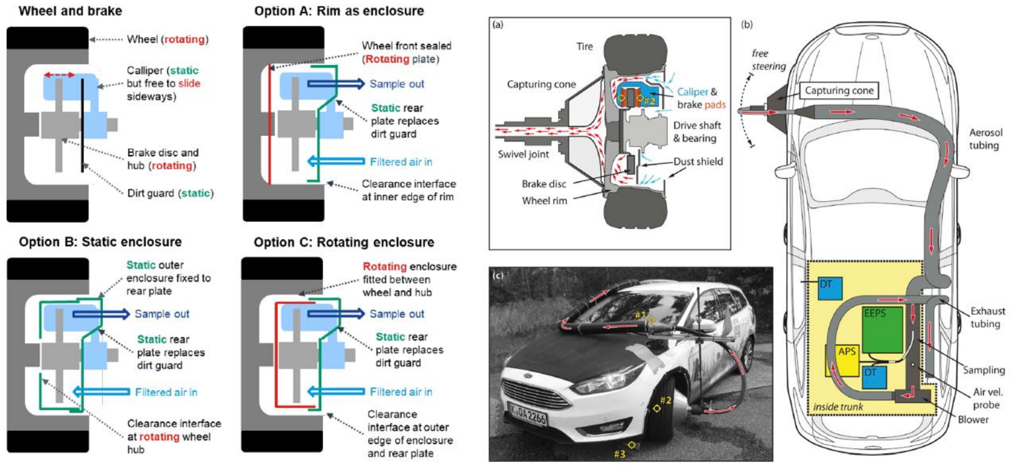


Fig. 4. Closed sampling system [14], [15]

The primary limitation of on-vehicle closed sampling systems for brake wear particulate measurement is their impact on the natural airflow and thermal conditions surrounding the brake components. In real-world driving, brakes are exposed to dynamic cooling from ambient air, which influences the temperature of the brake disc and pads, the wear rate, and the nature of particulate emissions. When the brake system is enclosed for sampling purposes, this natural ventilation is significantly reduced or eliminated, leading to elevated or inconsistent brake temperatures. These altered thermal conditions can change the physical and chemical properties of the wear particles produced, resulting in measurements that do not accurately reflect actual driving emissions.
Moreover, closed systems can interfere with the dispersion and deposition of brake particles. Particles may accumulate on the walls of the enclosure or be re-entrained into the airflow, which complicates accurate sampling and quantification. The enclosure may also create unnatural backpressure or airflow turbulence, further affecting particle behavior. These limitations reduce the ability of the system to capture true brake wear emission profiles under real driving conditions.

4. CONCLUSION

The accurate measurement of brake wear particulate emissions is crucial for understanding their environmental and health impacts, yet it remains a complex challenge due to the diverse methodologies employed and their inherent limitations. This non-exhaustive literature review highlights the strengths and limitations of the various existing techniques for measurement of BWPM. The development of harmonized testing protocols, such as those proposed by the UN GTR 24, represents a significant step toward standardizing measurement practices and facilitating cross-study comparisons.

Acknowledgement

This work was supported by Slovak Research and Development Agency under the Contract no. VV-MVP-24-0227.

References

[1] AROLE, K. et al. 2023. Impacts of particles released from vehicles on environment and health. Tribology International. Vol. 184. https://doi.org/10.1016/j.triboint.2023.108417.

[2] HESSE, D. et al. 2021.Testing of Alternative Disc Brakes and Friction Materials Regarding Brake Wear Particle Emissions and Temperature Behavior. Atmosphere. Vol. 12, No. 4. https://doi.org/10.3390/atmos12040436.

[3] LIU, Y. et al. 2022. Brake wear induced PM_{10} emissions during the world harmonised light-duty vehicle test procedure-brake cycle. *Journal of Cleaner Production.* Vol. 361. https://doi.org/10.1016/j.jclepro.2022.132278.

[4] HAGINO, H. 2024. Feasibility of Measuring Brake-Wear Particle Emissions from a Regenerative-Friction Brake Coordination System via Dynamometer Testing. Atmosphere. Vol. 15, No. 1, 75. https://doi.org/10.3390/atmos15010075.

[5] NEUKIRCHEN, C. 2025. Comprehensive elemental and physical characterization of vehicle brake wear emissions from two different brake pads following the Global Technical Regulation methodology. Journal of Hazardous Materials, Vol. 482. https://doi.org/10.1016/j.jhazmat.2024.136609

[6] CHASAPIDIS, L. et al. 2018. Study of Brake Wear Particle Emissions of a Minivan on a Chassis Dynamometer. Emission Control Science and Technology. Vol. 4., pp. 271-278. https://doi.org/10.1007/s40825-018-0105-7.

[7] MATHISSEN, M. et al. 2019. Brake Wear Particle Emissions of a Passenger Car Measured on a Chassis Dynamometer. Atmosphere. Vol. 10, No. 9. https://doi.org/10.3390/atmos10090556.

[8] BONDORF, L. et al. 2023. Airborne Brake Wear Emissions from a Battery Electric Vehicle. Atmosphere. Vol. 14, No. 3. https://doi.org/10.3390/atmos14030488.

[9] JOO, B. S. et al. 2019. Effects of binder resin on tribological properties and particle emission of brake linings. Wear. Vol. 434-435. https://doi.org/10.1016/j.wear.2019.202995.

[10] WAHLSTRÖM, J. 2019. A pin-on-disc tribometer study of friction at low contact pressures and sliding speeds for a disc brakes material combination. Results in Engineering. Vol. 4. https://doi.org/10.1016/j.rineng.2019.100051.

[11] Al WASIF-RUIZ, T. et al. 2025. Direct measurement of brake wear particles from a light-duty vehicle under real-world driving conditions. Environmental Science and Pollution Research. Vol. 32, pp. 2551–2560. https://doi.org/10.1007/s11356-024-35879-y.

[12] OROUMIYEH, F., ZHU, Y. 2021. Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity. Atmospheric Environment: X. Vol. 12. https://doi.org/10.1016/j.aeaoa.2021.100121.

[13] WANG, Y. et al. 2022. Assessing the brake particle emissions for sustainable transport: a review. Renewable and Sustainable Energy Reviews. Vol. 167. https://doi.org/10.1016/j.rser.2022.112737.

[14] ANDERSSON, J. et al. 2024. Practical Approach for On-Road Measurements of Break Wear Particles from a Light-Duty Vehicle. Atmospheres. Vol. 15, No. 2. https://doi.org/10.3390/atmos15020224.

[15] FARWICK ZUM HAGEN, F. H. et al. 2019. On-road vehicle measurements of brake wear particle emissions. Atmospheric Environment. Vol. 217. https://doi.org/10.1016/j.atmosenv.2019.116943.

Erik VARJÚ[1], Juraj KOVÁČ[2], Ján KOPEC[3]

DEVELOPMENT OF APPLICATIONS FOR TRAINING IN VIRTUAL REALITY ENVIRONMENT

Abstract

The objective of this paper is to present the development and evaluation of a virtual reality (VR) training application tailored to the needs of engineering education. The application makes use of modern VR technologies to replicate real-world technical tasks in a simulated environment, enabling the acquisition of practical skills through immersive, experience-based learning. A key focus is placed on the creation of a virtual workspace that supports the execution and training of fundamental engineering procedures, such as dimensional inspection and component handling. The paper outlines the design methodology, implementation process, and functional testing of the application, and provides a critical assessment of the potential benefits and limitations of VR integration in technical training contexts.

Key words: virtual reality, headset, data glove, CAD systems.

1 INTRODUCTION

In engineering, virtual reality is utilized at various stages of product design and manufacturing cycles. Designers and engineers first use it to assess potential, strengths, weaknesses, and features even before work begins on producing the physical product. This method allows testing how the product functions and examining its details before allocating corporate resources for its production, thereby saving time and money for the company. Engineers can test the product in a safe environment. The application of virtual reality in engineering enables the creation of a safe environment that is often challenging or even impossible to establish in the real world. As a result, all necessary adjustments can be made to refine the product to perfection before it reaches the production and assembly lines. Virtual reality has the ability to highlight details and reveal interferences that affect the operation of a product, allowing specialists to more quickly identify and resolve potential issues or even prevent them.

[1] Erik Varjú, Ing., Technical University of Košice, Faculty of Mechanical Engineering, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, Slovak Republic, erik.varju@tuke.sk

[2] Juraj Kováč, doc. Ing. PhD., Technical University of Košice, Faculty of Mechanical Engineering, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, Slovak Republic, juraj.kovac@tuke.sk

[3] Ján Kopec, Ing., Technical University of Košice, Faculty of Mechanical Engineering, Department of Industrial and Digital Engineering, Park Komenského 9, 040 01 Košice, Slovak Republic, jan.kopec@tuke.sk

2 MEANS OF VIRTUAL REALITY USED IN APPLICATION DEVELOPMENT

A It is assumed that 80% of the information a person acquires is visual. Therefore, developers of virtual reality systems pay great attention to devices that ensure image creation. These devices are typically complemented by stereo sound systems, and there is ongoing work on tactile effects and even the imitation of scents. Modern virtual reality headsets (HMD displays, head-mounted displays, video helmets) contain one or more screens that display images for the left and right eye, a lens system for adjusting image geometry, and a tracking system that monitors the device's orientation in space. These headsets [
Fig. 1]resemble glasses in appearance and are increasingly referred to as VR headsets or simply virtual reality glasses [1].

Fig. 1. Headset Meta Quest 3 [2]

VR headsets can be divided into three categories:
1. Glasses in which the processing and display of images are provided by a smartphone.
2. Glasses in which image processing is handled by an external device.
3. Autonomous glasses for virtual reality.

Another important aspect of immersing oneself in virtual reality is sound. A multi-channel acoustic system enables the localization of sound sources, allowing the user to navigate through the virtual world using their hearing. No less significant are the tactile sensations that are conveyed through special suits and gloves. These gloves are equipped with sensors that allow monitoring of the user's hand and finger movements. Technically, this can be achieved using various methods, such as optical fiber cables, strain gauges, piezoelectric sensors, or electromechanical devices (such as potentiometers). For instance, researchers from EPFL and ETH Zurich have developed ultra-lightweight gloves weighing less than 8 grams per finger and only 2 mm thick. These gloves provide 'extremely realistic haptic feedback' and can be powered by batteries, ensuring unprecedented freedom of movement [1].

3 SOFTWARE SUPPORT FOR THE CREATION OF VR APPLICATIONS

SolidEdge

Solid Edge is a 3D CAD (Computer-Aided Design) software developed by Siemens, offering parametric and direct modeling tools for mechanical engineering, product design, and manufacturing. It features synchronous technology for faster edits, simulation capabilities, sheet metal design, and assembly management, supporting industries like aerospace, automotive, and industrial machinery. Available in both cloud and on-premise versions, it integrates with PLM (Product Lifecycle Management) systems for end-to-end product development [2].

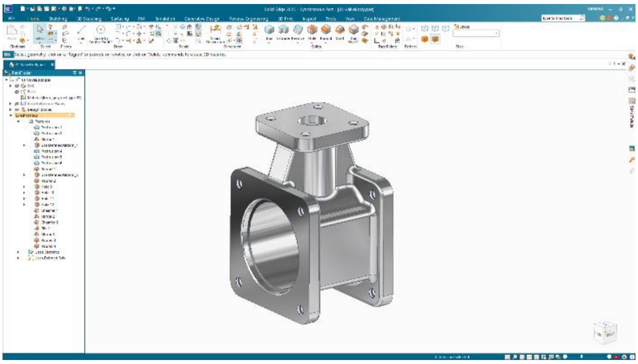


Fig. 2. SolidEdge Interface

Pixyz Review

Pixyz Review is part of a larger suite of Pixyz products, including Pixyz Studio, Pixyz Batch, and Pixyz Plugin, which offer cutting-edge solutions for the preparation, optimization, and management of large CAD data. 3D CAD files typically require access to complex and often expensive software. Pixyz Review is capable of processing large and intricate files, visualizing 3D models of any type (mesh, CAD, or point cloud) or size in a leading range of over 50 file formats, including CATIA, NX, SolidEdge, and others. Visualization and immersion into virtual reality can be set up in less than ten minutes, and any user can master the solution within a few hours, regardless of their technical expertise. In addition to virtual collaboration capabilities, Pixyz Review is compatible with most VR headset setups, supports metadata and PMI/FTA on 3D models, and includes useful additional features such as plane cutting and measurement options [4].

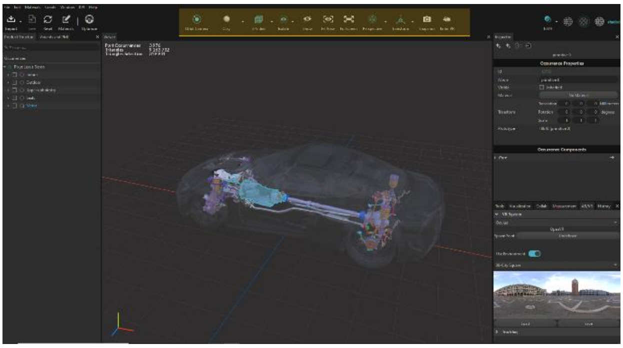


Fig. 3. Pixyz Review Interface

4 PROPOSAL FOR A SPECIFIC VR APPLICATION FOR MEASUREMENT SIMULATIONS

In order to simulate the measurement processes for quality technicians, derived from actual production, in virtual reality, models of real objects were created using the CAD software SolidEdge. A total of 2 types of tables were created using the software. The first table is made of aluminum, on which measuring instruments and a height gauge are placed. The second table is a special metal measuring device used to measure the flow of objects.

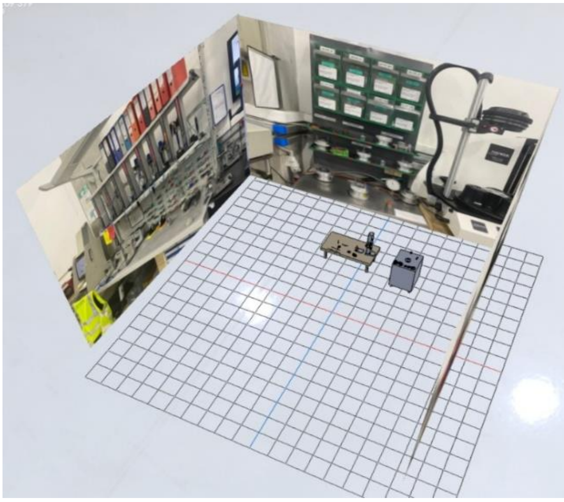


Fig. 4. VR Application's Virtual Environment

When transferring models to virtual reality, the movement parameters of individual components and their parts were set to allow for their further movement along predetermined axes in accordance with their purpose and the described measurement processes.

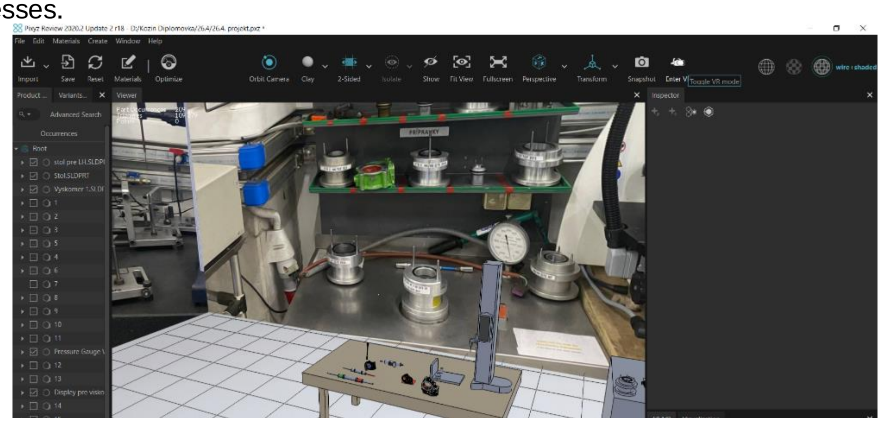


Fig. 5. Imported 3D Models in Pixyz Review

Around the testing site in virtual reality, a representation of the actual working environment in manufacturing has been implemented, utilizing real photographs of the production space.

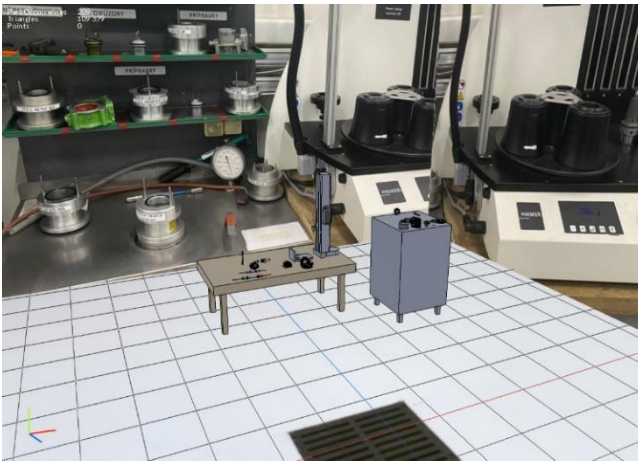


Fig. 6. First-person perspective in a testing environment

After transferring the models to virtual space, setting the positions of objects, motion parameters, as well as creating textures and the appearance of the simulation space in virtual reality using a virtual reality manipulation device (glasses and control handles), the entire measurement process was tested (Fig. 6) in accordance with the regulatory documents of the company for which the application was developed. With the headphones integrated into the virtual reality glasses, audio instructions can also be incorporated into the learning process.

Fig. 7 The process of testing measurement processes in virtual reality

A demonstration of the environment display and simulation of work in virtual reality during the process of measuring the tolerances of individual components using Pixyz Review software (Fig. 7).

5 CONCLUSION

Virtual reality represents an innovative and effective tool for enhancing educational processes, particularly in the field of technical and engineering training. The creation of an application for simulating measurement processes, as demonstrated in this article, provides a practical approach to education that is interactive and realistic. The use of virtual reality technology allows for the creation of safe, simulated environments where participants can practice various measurement techniques without risk and with immediate feedback. Virtual reality technologies not only increase the effectiveness of learning but also the readiness of workers for real-world job challenges. In the future, further development of virtual applications can be expected, enabling even broader integration into the educational process, thus reinforcing their significance in vocational and technical education.

Acknowledgment

The article was developed within the projects APVV-17-0258 – Digital engineering elements application in innovation and optimization of production flows, APVV-19-0418 – Intelligent solutions to enhance business innovation capability in the process of transforming them into smart businesses, VEGA 1/0508/22 – Innovative and digital technologies in manufacturing and logistics processes and systems, VEGA 1/0383/25 – Optimizing the activities of manufacturing enterprises and their digitization using advanced virtual means and tools, KEGA 020TUKE-4/2023 – Systematic development of the competence profile of students of industrial and digital engineering in the process of higher education, KEGA 003TUKE-4/2024 – Innovation of the profile of industrial engineering graduates in the context of required knowledge and specific capabilities for research and implementation of intelligent systems of the future.

References

[1] KOVÁČ, J., RUDY, V.: Use of virtual reality in assembly processes - 2021. In: Trends and Innovative Approaches in Business Processes 2021= Trendy a inovatívne prístupy v podnikových procesoch 2021 : 24th International Scientific Conference. – Košice

[2] Meta Quest 3 – Všetko, čo vieme. Available online: https://www.alza.sk/meta-quest-3-info

[3] KOPEC, J., KOVÁČ. J., PEKARČIKOVÁ, M., MIZERÁK, M.: Digitalization of 3D Laboratory in Virtual Reality -2022. In: InvEnt 2022. Invention for Enterprise. - Žilina (Slovensko) : Žilinská univerzita v Žiline s. 56-61 [online]. - ISBN 978-80-970974-4-8

[4] KOVÁČ, J., MALEGA, P., RUDY, V.: Využitie zmiešanej reality v procese montáže a demontáž súčiastok - 2022. In: Průmyslové inženýrství 2022: Sborník příspěvků z mezinárodní studentské vědecké konference. - Plzeň (Česko) : Západočeská univerzita v Plzni s. 84-90 . – ISBN 978-80-261-1114-6

[5] RUDY, VLADIMÍR; KOVÁČ, JURAJ; MALEGA, PETER.: Projektovanie výrob budúcnosti: Modelovanie a virtuálna realita v priemyselnej praxi. 1. vyd. Košice: SjF TU v Košiciach. 2022. ISBN 978- 80-553-4186-6.

Ján ZUZIK[1], Ľuboslav DULINA[2], Beáta FURMANNOVÁ[3]

THE ROLE OF ERGONOMICS IN THE INDUSTRY 5.0 ERA

Abstract

The purpose of this article is to examine the importance of ergonomics in Industry 5.0, which recognizes the importance of humans, sustainability, and resilience (as opposed to robotic automation, like in Industry 4.0), and demonstrates how ergonomics, both physical and cognitive, can enhance worker comfort, safety, and well-being in modern workplaces that include a range of new technology. The article outlines potential application challenges and opportunities with ergonomics in complicated, and sometimes unpredictable, human-machine interactions, with a focus on human-robot collaboration. Finally, it looks at the role of artificial intelligence (AI) in facilitating the optimization of work environments and more safely and efficiently managing human-robot interaction. Increased attention is devoted to this topic as it forms a part of the dissertation research.

Key words: industrial engineering, ergonomics, Industry 4.0, Industry 5.0

1. INTRODUCTION

The concept of Industry 5.0 arose as a desire to rethink and orient industry in Europe and a global context. Industry 4.0 had many successful new advances in automation and digital technologies, but in doing so overlooked several major areas, and in particular, the human component and the workers in factories [1, 2]. The European Commission launched Industry 5.0 as an innovative way of thinking by the industry to respond to significant economic and social challenges occurring today, where climate change, resource scarcity, and global catastrophes such as the COVID-19 pandemic are recurrent issues [3].

Industry 5.0 is responsive to three important conceptual pillars, namely: human-centeredness, sustainability, and resilience [3, 4]. In this sense, ergonomics (designing work, tools, and work environments for human capabilities and limitations) is a relevant

[1] Ján Zuzik, Ing., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, jan.zuzik@fstroj.uniza.sk

[2] Ľuboslav Dulina, prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, luboslav.dulina@fstroj.uniza.sk

[3] Beáta Furmannová, assoc. prof. Ing. PhD., University of Zilina, Faculty of Mechanical Engineering, Department of Industrial Engineering, Univerzitna 8215/1, 010 26 Zilina, Slovakia, beata.furmannova@fstroj.uniza.sk

dimension. Ergonomics will help to design for the human factor of industrial ecosystems and is central to successfully implementing human-centeredness in Industry 5.0 [5].

The purpose of this article is to look at the connection between ergonomics and Industry 5.0, examine the possible challenges of applying ergonomics to next-generation industrial ecosystems, and propose ways to maximize the workplace and working conditions for employees in an Industry 5.0 environment. The topic of this work is highly topical and is also given attention in the framework of the dissertation [6].

2. THE CONCEPT OF INDUSTRY 5.0 AND ITS CHARACTERISTICS

Industry 5.0 is the next stage in development after Industry 4.0. The 4.0 paradigm shift promoted automation and digital technology, and the 5.0 paradigm shift is about the collaboration of people and machines as partners [19]. The main premise of Industry 5.0 is the unique role of human creativity, intelligence, and problem-solving for complex matters [2, 7]. Industry 5.0 takes a broader view of production than Industry 1-4 revolutions had taken. Rather than only focusing on technology and increased productivity, Industry 5.0 acknowledges society and the environment as legitimate concerns for industry [8, 9].

The three pillars of Industry 5.0 are: people-centredness, sustainability, and resilience. People-centredness means imagining a future in which industry not only applies the latest technological capacity well, but also contributes to society, and allows workers to maintain or improve their quality of life. People-centredness means fundamentally reconsidering how technology works in tandem with human ability so it supports human ability, instead of undermining it [2, 4, 10].

Industry 5.0 has expanded the often prescriptive objectives of efficiency and productivity to allow a richer purpose, to also include societal good. This transition is particularly timely, as we face dire challenges such as climate change, scarcity of human resources, and crisis-prone industrial systems [11].

3. PHYSICAL AND COGNITIVE ERGONOMICS IN INDUSTRY 5.0

Ergonomics has two dimensions in Industry 5.0: physical and cognitive. Physical ergonomics has a long history in attempts to create better work circumstances whereby workers spend less time in discomfort, fatigue, and physical stress. To achieve this, it is necessary to consider designs for better workstations, unintended working postures and movements, and preventing musculoskeletal disorders [12].

Cognitive ergonomics, which has increased importance in Industry 5.0, considers the mental and cognitive demands of work. Work is becoming increasingly complex due to changes in technology and work processes, and therefore, consideration must be given to how people process information, make decisions, and collaborate with intelligent systems. Cognitive ergonomics seeks to optimize human-machine interfaces, cognitively offload human processing, and support decision-making [13].

The integration of physical and cognitive ergonomics is critical in the work environment to both protect health and promote employees' well-being, motivation, and satisfaction. In Industry 5.0, ergonomically designed workplaces must be designed such that technology is intended to serve people's fundamental work requirements. Today's more advanced ergonomic solutions (exoskeletons, wearable sensors, virtual and augmented reality) can help create better working conditions and improved work efficiency [12, 13].

Artificial intelligence (AI) is becoming an essential tool in applying ergonomic principles for Industry 5.0. AI can monitor work processes, assist with the identification of ergonomic risks, and suggest real-time optimization of the work environment. Computer vision and machine learning based systems can monitor worker movements and notify when potentially harmful situations or work practices conflicting with ergonomic principles are observed [12, 13, 14].

4. HUMAN-ROBOT COLLABORATION IN THE CONTEXT OF ERGONOMICS

One key aspect of Industry 5.0 is the idea of people and robots collaborating, rather than trying to completely automate work. Collaboration between humans and robots, known as human-robot collaboration (HRC), is a new form of industrial automation in which robots and people work together by combining robots' strength and precision with humans' creativity, flexibility, and decision-making [13, 15].

From an ergonomics perspective, the disadvantages of human-robot collaboration are substantial because robots can perform arduous, repetitive, and unsafe tasks on behalf of workers, reducing the probability of sustaining an injury, illness, or any other harm caused by work. Of course, collaborative robots (or cobots) are designed to improve safety when working closely with humans while assisting their work in a shared workspace [13, 14].

However, for human-robot collaboration to occur safely and effectively, it is very important to communicate effectively through ergonomics principles and implement the potentially negative ergonomic aspects of human-robot collaboration. Ergonomics can ensure that working with robots is desirable (easy, safe, and comfortable) for people and accounts for user-friendly interface controls, the organization of the shared workspace, and safety protocols to reduce the probability of an incident occurring [14, 15].

Cognitive ergonomics is also very important when designing situations where humans and robots and robots are working as a team. Communication between humans and robots must be explicit and easily understood to allow humans to predict, in the best way possible, what the robot will do. The cognitive load must also be such that the workflow between the human and the automated systems are not taxing the human too much [14, 15].

5. ERGONOMICS CHALLENGES AND OPPORTUNITIES IN INDUSTRY 5.0

There are several key difficulties associated with applying ergonomic principles in Industry 5.0. One difficulty is that existing ergonomic methods and tools will have to be developed for new technologies and work processes, which is not easy. For example, it will be increasingly more difficult to anticipate how people and technology will converge, as systems get more complex, in ways that might affect ergonomics outcomes [16].

Another difficulty is that ergonomics requires a holistic approach. It is not just about the physical environment; it is also about the mental, emotional, and social aspects of work. In the context of Industry 5.0, it is not enough to thoughtfully consider the physical workspace. It is equally important to contemplate how workplace conditions translate into mental well-being, motivation, and satisfaction [17].

A further challenge is the data collection and analysis to drive change in ergonomic conditions. Modern technology can record and capture a great deal of information about the workplace and workers' performance, but utilizing this information appropriately for ergonomics requires sophisticated tools and expert knowledge [16, 17].

However, Industry 5.0 also provides new opportunities for ergonomics. New technologies like augmented and virtual reality can be used to simulate and test ergonomic solutions without the need for real prototypes. Artificial intelligence can analyze complex patterns of human behavior and suggest personalized ergonomic recommendations [16, 17].

One opportunity is to use Industry 5.0 technologies in a way that results in more inclusive workplaces. This means enabling people with different disabilities or special needs to participate in work. Various types of assistive technologies, exoskeletons, and smart workplaces can enable people with physical limitations to take part in work with their skills and knowledge [16, 17].

6. CONCLUSION

Industry 5.0 represents a significant shift in how we understand the role of people in industry. While earlier industrial revolutions have focused on technology and productivity, Industry 5.0 focuses on people, people's needs, people's abilities, and ultimately, people's well-being. This is where ergonomics will become increasingly important; ergonomics can help to contribute to a good human-technology-work system relationship [14, 17].

By definition, ergonomics has two principal aspects: physical ergonomics, for preventing physical risk and improving health outcomes for workers, and cognitive ergonomics, which is considered more about workers' mental and thinking components. This is also especially relevant as workplace systems and their respective technologies become increasingly complex [12, 17].

Working side-by-side with robots is one aspect of the Industry 5.0 paradigm. Working with robots may improve workplace ergonomics, but it can also create safety and comfort challenges. The challenge is to design workplaces in which technologies genuinely help people reduce stress, rather than adding to their stress [17].

In conclusion, ergonomics is not only about risk reduction and illness prevention in Industry 5.0. It is also about helping to realize people's potential and creativity and promoting people's well-being. To make Industry 5.0 sustainable, resilient, and people-centered, it is vital to utilize ergonomic principles in the design of industrial systems [17,18].

Acknowledgement

This work was supported by the KEGA Agency under the contract no. 001ŽU-4/2024.
This work was supported by the KEGA Agency under the contract no. 013ŽU-4/2025.

References

[1] TRSTENJAK, M., OPETUK, T., ĐUKIĆ, G., CAJNER, H. 2025. Use of Artificial Intelligence (AI) in the Workplace Ergonomics of Industry 5.0. Tehnički Glasnik, 19(2), 335–340. https://doi.org/10.31803/tg-20250105140152
[2] SINGH, D.: The Economics of Drone Delivery. What Is Industry 5.0 And Its Human-Centric Approach? eLearning Industry. 2024. Available on the internet: https://elearningindustry.com/what-is-industry-5-0-and-its-human-centric-approach
[3] Veda na dosah: Industry 5.0: Od teórie do praxe. Veda na dosah. 2025. Available on the internet: https://vedanadosah.cvtisr.sk/podujatie/industry-5-0-od-teorie-do-praxe/
[4] MAĽA, P: Priemysel 5.0 a budúcnosť práce. Elektronická platforma vzdelávania dospelých v Európe. 2023. Available on the internet: https://epale.ec.europa.eu/sk/resource-centre/content/priemysel-50-buducnost-prace
[5] GUALTIERE, L., FRABONI, F., BRENDEL, H., PIETRANTONI, L., VIDONI, R., DALLASEGA, P. 2024. Updating design guidelines for cognitive ergonomics in human-centred collaborative robotics applications: An expert survey. Applied Ergonomics, 117, 104246. https://doi.org/10.1016/j.apergo.2024.104246
[6] DULINA, L. 2023. Uplatnenie ergonómie vo výrobných a logistických systémoch. Žilinská univerzita v Žiline: EDIS. 2023. 106 s. 978-80-554-1960-2.
[7] BOLIS, I., MORIOKA, S. N., BRUNURO, C. M., ZAMBRONI-DE-SOUZA, P. C., SZNELWARS, L. I. (2020). The centrality of workers to sustainability based on values: Exploring ergonomics to introduce new rationalities into decision-making processes. Applied Ergonomics, Vol. 88, 103148
[8] KRAJCOVIC, M., GABAJOVA, G., MATYS, M., FURMANNOVA, B., DULINA, L. 2022. Virtual Reality as an Immersive Teaching Aid to Enhance the Connection between Education and Practice. Sustainability, Vol. 14(15), Article 15. https://doi.org/10.3390/su14159580.
[9] CORLETT, E. N., STAPTELON, C. 2001. The Ergonomics Society: 50 years of growth. Ergonomics, Vol. 44(14), 1265–1277. https://doi.org/10.1080/00140130110105869.
[10] KOPŘIVA, T. Význam ergonómie pre vývoj moderných a zdravých priemyselných pracovísk. Asseco CEIT. 2024. Available on the internet: https://www.asseco-ceit.com/sk/vyznam-ergonomie-pre-vyvoj-modernych-a-zdravych-priemyselnych-pracovisk/
[11] Springer Professional: Cognitive Ergonomics in Industry 5.0 | springerprofessional.de. 2025. Available on the internet: https://link.springer.com/chapter/10.1007/978-3-031-38165-2_88
[12] SVOZILOVA, A. 2011. Zlepšovaní podnikových procesů. Grada Publishing. 2011. 232 s. ISBN 978-80-247-3938-0.
[13] PARSONS, K., SHACKEL, B., METZ, B. 1995. Ergonomics and International Standards—History, Organizational-Structure and Method of Development. Applied Ergonomics, Vol. 26(4), 249–258. https://doi.org/10.1016/0003-6870(95)00028-B.
[14] MICIETA, B., BINASOVA, V., MARCAN, P., GASO, M. 2023. Interfacing the Control Systems of Enterprise-Level Process Equipment with a Robot Operating System. Electronics, Vol. 12(18), Article 18. https://doi.org/10.3390/electronics12183871.

[15] SLAMKOVA, E., DULINA, L., TABAKOVA, M. 2010. Ergonómia v priemysle. GEORG kníhárstvo. 2010. 262 s. ISBN 978-80-89401-09-3.

[16] BRITO, M. F., RAMOS, A. L., CARNEIRO, P., & GONCALVES, M. A. 2020. A continuous improvement assessment tool, considering lean, safety and ergonomics. International Journal of Lean Six Sigma, Vol.11(5), 893–916. https://doi.org/10.1108/IJLSS-12-2017-0144.

[17] ANTONACI, F. G., OLIVETTI, E. C., MARCOLIN, F., CASTIBLANCO JIMENEZ, I. A., EYNARD, B., VEZZETTI, E., MOOS, S. 2024. Workplace Well-Being in Industry 5.0: A Worker-Centered Systematic Review. Sensors, 24(17), Article 17. https://doi.org/10.3390/s24175473

[18] GYURÁK BABELOVÁ, Z., VRAŇAKOVÁ, N., STAREČEK, A. 2025. Development of Intellectual Potential with Regard to Industrial Engineering Research. MM Science Journal, March 2025, pp. 8100–8107. https://www.mmscience.eu/journal/issues/march-2025/articles/development-of-intellectual-potential-with-regard-to-industrial-engineering-research

[19] STAREČEK, A., GYURÁK BABEĽOVÁ, Z., VRAŇAKOVÁ, N., JURÍK, L. 2023. The Impact of Industry 4.0 Implementation on Required General Competencies of Employees in the Automotive Sector. Production Engineering Archives, 29(3), pp. 254–262. https://doi.org/10.30657/pea.2023.29.29

ISBN 978-83-947909-9-8
9 788394 790998