# SZÉCHENYI ISTVÁN UNIVERSITY PROCEEDINGS OF SUSTAINABLE DEVELOPMENT RESEARCH

## 2nd Conference on Sustainability – COS 2024
## 06-09 November 2024, Győr, Hungary

**COS2024**


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PETAR S. VARBANOV, BOHONG WANG,
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# EXAMINING THE ROLE OF SUSTAINABILITY METRICS IN ADVANCING SUSTAINABLE CONSTRUCTION PROJECT MANAGEMENT

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**In recent years, sustainable project management practices have become increasingly important. Sustainability indicators are key tools for guiding construction projects toward their sustainability objectives. This study aims to identify and prioritize the most crucial sustainability indicators that contribute to sustainable construction projects, taking into account the perspectives of various construction project stakeholders. To achieve this goal, a research design was used, which involved a questionnaire survey to assess the views of construction sector stakeholders on the use of sustainability indicators to achieve sustainability goals in their projects. The structured questionnaire included 82 pre-identified indicators, drawn from relevant literature and expert input. Data analysis employed the relative importance index approach, commonly utilized for similar purposes in the literature. The results indicated that environmental indicators were the most significant. These findings offer valuable insights for practitioners looking to enhance sustainability in the construction sector by focusing on, implementing, and monitoring the most impactful indicators.**

## 1. Introduction

The construction industry faces criticism for its environmental impact, presenting an opportunity to contribute to global sustainability efforts (Svajlenka and Kozlovska, 2020). While various approaches exist to achieve this, project sustainability remains complex because of differing stakeholder perspectives (Salmi, et al., 2022). This study proposes a stakeholder-centric approach using relevant indicators to improve project sustainability performance.

Sustainability in construction is multifaceted, encompassing economic, environmental, and social aspects (Lee, et al., 2019). Integrating sustainability principles into construction projects aims for "triple-bottom-line" (TBL) improvements across these dimensions. This approach aligns with the growing adoption of TBL policies within the industry (Rodriguez et al., 2020). Sustainable development (SD) emphasizes environmental conservation, economic progress, and social development in construction. Stakeholder perspectives on sustainability indicators are crucial for minimizing negative effects and enhancing performance. (Awalunnisa, et al., 2023) Global policies and regulations promote implementing sustainability at a strategic level. Agenda 21, a prominent sustainability framework, highlights the need for indicators to achieve sustainable objectives (U.N., 1992).

This study aims to identify and prioritize the most important indicators for sustainable project management, considering the perspectives of various construction stakeholders. The three TBL dimensions (economic, environmental, and social) were used to categorize indicators from previous studies. Experts in sustainability, construction, and project management collaborated to develop and distribute a survey for ranking these indicators. The survey captured the viewpoints of seven stakeholder groups, including clients, users,

manufacturers, contractors, designers/consultants, authorities/government, and researchers. The Relative Importance Index (RII) was used to measure the influence of each stakeholder category on each indicator.

This ranking process can enhance the effectiveness of sustainable construction project management practices. The findings can benefit construction stakeholders and future researchers by providing a framework for utilizing sustainability indicators in project management to achieve sustainable construction. While universally confirming the application may be challenging, this study is a valuable reference for practitioners to prioritize specific indicators and contribute to implementing sustainability in their projects. The inclusion of international expert perspectives fosters the development of a widely applicable set of sustainability indicators for project management in construction.

# 2. Literature review

The concept of sustainable construction emerged in the 1990s, marking a shift towards environmentally conscious practices in the industry (Kibert, 1994). Internationally recognized systems like BREEAM and LEED encourage sustainable construction. However, research highlights the need for further exploration in this developing field (Wang, 2021).

## 2.1. Sustainability Indicators: A Balancing Act

The construction industry must prioritize sustainability and implement sustainability indices to measure performance. Key aspects, such as comprehensiveness, practicality, life-cycle approach, and project focus, should be considered to create a sound evaluation system (Sajjad et al., 2023). Balancing economic, environmental, and social aspects is crucial when assessing sustainability.

## 2.2. Stakeholder Engagement and Indicator Identification

The participation of stakeholders in defining indicator sets is necessary, and studies demonstrate their involvement in indicator development (Vermeulen, 2018). Through stakeholder engagement, some studies have identified indicators of social sustainability (Karji, et al., 2019). This research contributes by analyzing project execution, outcomes, and operating environment indicators affecting the TBL of construction projects.

## 2.3. Project Manager and Sustainability

Project managers play a vital role in prioritizing sustainability. Baccarini defines CSFs as tools for faster, more effective project execution (Baccarini and Collins, 2003). By monitoring economic volatility, social acceptance, and eco-efficiency indicators, project managers can make informed decisions for project success (Kaufmann and Kock, 2022). Our research focuses on this gap, examining the link between stakeholders and sustainable project management indicators for construction projects.

## 2.4. Stakeholder Identification

Following PMI standards, stakeholders include individuals or organizations impacted by a project (PMI, 2017). Yang and Shen identified 14 stakeholder categories, while Williams and Dair outlined four major groups (Yang and Shen, 2015; Williams and Dair, 2007). This research focuses on seven key stakeholder groups for sustainable construction: clients, users, manufacturers, contractors, designers/consultants, authorities/government, and research academics. This distinction reflects the significant influence these groups hold on sustainable construction practices. Stakeholder theory emphasizes balancing stakeholder benefits to achieve sustainable construction. Effective stakeholder management requires clear communication. Our research identifies relevant, sustainable project management indicators and gathers stakeholder perspectives to address this challenge.

# 3. Research methodology

As part of a wider research effort, this study utilizes a quantitative research method based on Knowledge-Based Theory (KBT) and follows a sequential approach outlined in Figure 1. The study draws on both qualitative and quantitative data from prior research as input.

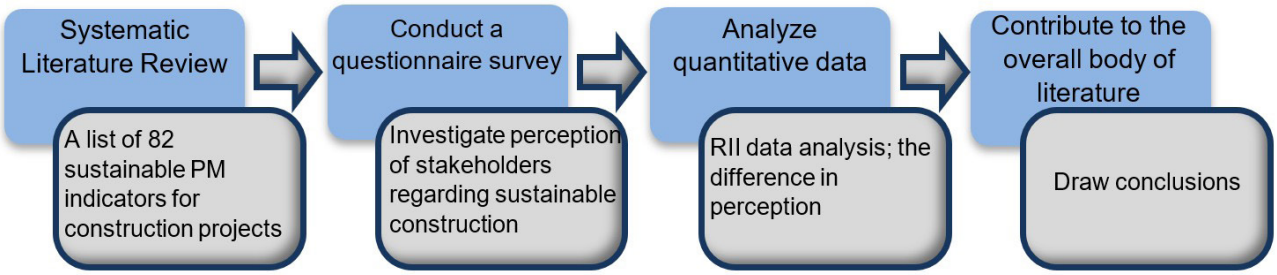



*Figure 1: Research design*

The primary objective of this research is to identify the most suitable sustainable project management (PM) indicators for construction projects. To this end, a systematic literature review (SLR) and semi-structured interviews were conducted to generate a list of 82 indicators. The authors emphasized the versatility of this list, which can be applied to various contexts or tailored to specific cases. This viewpoint suggests that the indicators for measuring sustainability in construction projects should be customized according to the specific project idea. Furthermore, the authors sought input from industry experts with over 10 y of experience to review and validate the final list of indicators, making it even more practical (Fernandez and Rodriguez, 2010).

The study involves an online survey questionnaire aimed at exploring the beliefs of various stakeholders (as identified in the literature review) regarding the significance of predetermined indicators. This research approach allows for the collection of data from a vast global sample in a non-intrusive, cost-effective, practical, and straightforward manner. Additionally, it helps minimize any bias that may arise from researchers' verbal or visual cues (Gunduz, 2016). The questionnaire employed an ordinal measurement scale (Likert scale) that ranks the importance of each indicator in ascending order from 1 to 5. Previous studies on similar topics have often utilized the questionnaire survey method (Torabizadeh et al., 2020).

Following the completion of the questionnaire, the data collected was carefully analyzed to determine the significance of the 82 indicators. To achieve this, the relative importance index (RII) formula, a non-parametric technique frequently utilized by construction and sustainability management scientists, was employed. This technique proves to be particularly valuable when working with data involving ordinal measurement of attitudes, such as stakeholders' views expressed through structured questionnaire responses (Waris, et al., 2014).

# 4. Instrument and respondents' profile

The survey instrument was designed based on categorized indicators, and participants rated the importance of each sustainable project management (SPM) indicator on a 5-point Likert scale. Data was collected from global thematic experts, and 157 responses were ultimately analyzed (Figure 2).

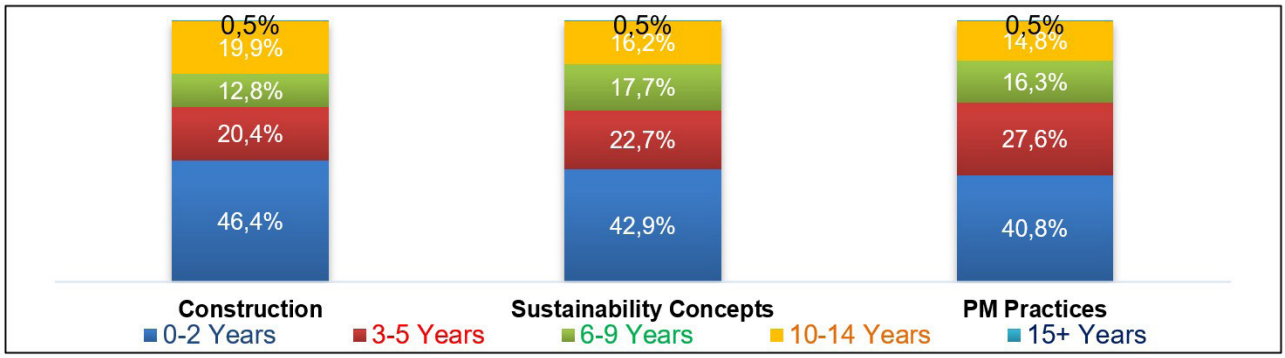



*Figure 2: Questionnaire data/previous experience on the themes analyzed*

Demographic information was collected to enhance analysis, and the research aimed to explore the relative importance of SPM indicators from the perspectives of various construction stakeholders with relevant professional experience. Analysis suggests a majority of respondents from the private sector have considerable work experience, indicating valuable contributions to the study's outcome.

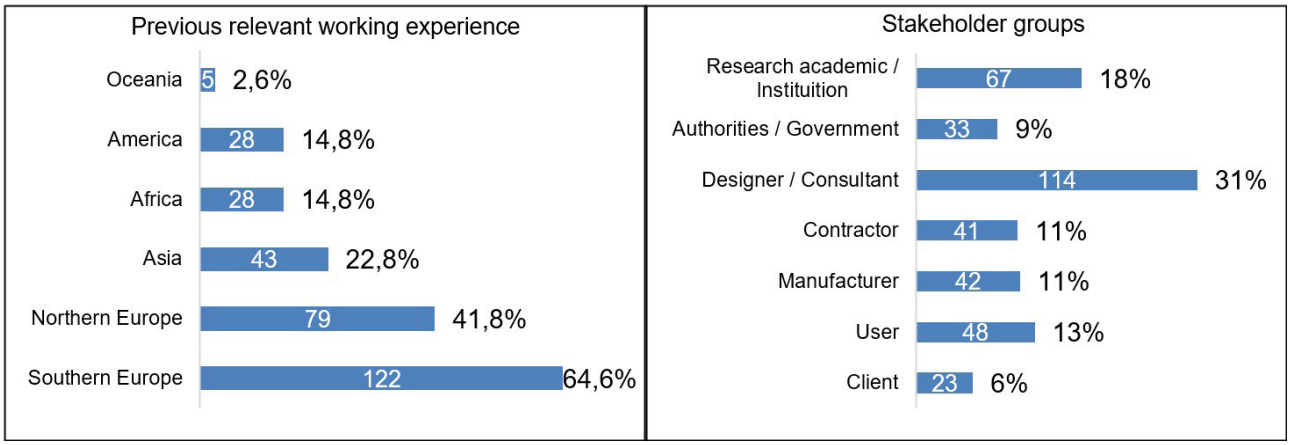



*Figure 3: Questionnaire data/continent experience and stakeholder categories*

# 5. Data analysis (RII)

The Relative Importance Index (RII) method (Olomolaiye et al., 1987) was used to determine the significance of sustainable PM indicators. Respondents rated each indicator on a 5-point Likert scale (1 = slightly important, 5 = very important). Microsoft Excel facilitated data analysis. Equation 1 calculated the RII score for each indicator (Waris et al., 2014).

$$RII = \frac{\sum_{i=1}^{5} w_i n_i}{A*N} = \frac{5n_5+4n_4+3n_3+2n_2+1n_1}{5*N} \quad (1)$$

- W shows the weighting value of each indicator, given by the respondent
- A is the highest weight
- N is the total number of respondents
- $n_i$ is the total number of responses that were evaluated with the number i (i= 1 to 5/Likert scale)

According to the respondents, the RII value indicates the level of importance of each indicator for sustainable construction projects. Higher RII values correspond to more significant indicators. The RII value ranges from 0 to 1, excluding 0. Akadiri (2011) categorizes the resulting RII importance levels as follows:

- High (H): 0.8 < RII < 1.0
- High-Medium (H-M): 0.6 < RII < 0.8
- Medium (M): 0.4 < RII < 0.6
- Medium-Low (M-L): 0.2 < RII < 0.4
- Low (L): 0 < RII < 0.2

Tables 1, 2, and 3 categorize the 82 indicators according to the TBL framework (economic, environmental, social/management) for clarity. All indicators were ranked as "High" or "High-Medium" importance, highlighting their critical role in sustainable construction projects. "High" importance indicators (RII scores: 0.802-0.901) spanned all TBL dimensions, suggesting stakeholder emphasis on TBL principles for sustainable development.

*Table 1: Pool of sustainable PM indicators for construction projects of economic sustainability*

| Indicator | RII | Ranking by category | Overall ranking | Importance level |
|---|---|---|---|---|
| ECO1: Financial/Economic performance | 0.871 | 2 | 7 | H |
| ECO2: Economic and Political Stability | 0.820 | 13 | 31 | H |
| ECO3: Stakeholder involvement/ participation | 0.847 | 9 | 19 | H |
| ECO4: Innovation management/new product development | 0.855 | 6 | 14 | H |
| ECO5: Target marketing and benefits | 0.765 | 22 | 63 | H-M |
| ECO6: Effective Project Control | 0.856 | 5 | 12 | H |
| ECO7: Best practice strategy | 0.850 | 7 | 16 | H |
| ECO8: Efficient allocation of resources | 0.873 | 1 | 5 | H |
| ECO9: Customer-relationship management/ Access to a range of customers | 0.755 | 24 | 67 | H-M |
| ECO10: Scope control through managing changes | 0.762 | 23 | 64 | H-M |
| ECO11: Business ethics | 0.775 | 18 | 56 | H-M |
| ECO12: Facility management technologies/ general improvements | 0.784 | 16 | 51 | H-M |
| ECO13: Cost management plan | 0.869 | 3 | 8 | H |
| ECO14: Resource planning | 0.846 | 10 | 20 | H |
| ECO15: Supply chain collaboration | 0.774 | 19 | 57 | H-M |
| ECO16: Effective strategic planning | 0.828 | 11 | 26 | H |
| ECO17: Organizational culture | 0.772 | 20 | 58 | H-M |
| ECO18: Project outputs emphasis | 0.780 | 17 | 53 | H-M |
| ECO19: Developing efficient "iron triangle" parameters by the PM Team | 0.766 | 21 | 61 | H-M |
| ECO20: Ability to pay and affordability | 0.848 | 8 | 18 | H |

| | | | | |
|---|---|---|---|---|
| ECO21: Environmental/economics accounting | 0.865 | 4 | 10 | H |
| ECO22: Developing an efficient risk management plan by the PMT | 0.802 | 15 | 41 | H |
| ECO23: Implementing an effective change management strategy | 0.802 | 14 | 40 | H |
| ECO24: Efficient data processing for decision-making practices | 0.821 | 12 | 30 | H |
| ECO25: Bureaucratic streamlining | 0.752 | 25 | 68 | H-M |
| ECO26: Internationalization | 0.712 | 26 | 78 | H-M |
| ECO27: Targeted incentives | 0.667 | 27 | 80 | H-M |

The study revealed that designers/consultants demonstrated the highest familiarity with sustainable PM practices, while authorities/government stakeholders were the least familiar. This suggests a need for increased government incentive policies to support sustainability efforts.

All stakeholders deemed environmental policies valuable. Notably, contractors and manufacturers prioritized economic indicators (e.g., ECO1: Financial/Economic performance, ECO13: Cost management plan), potentially reflecting profit-driven strategies amidst rapid urbanization and challenges adapting to sustainable practices (Mensah et al., 2018). Users valued social indicators but ranked them lowest overall.

Interestingly, research academics primarily focused on environmental factors, prioritizing related indicators for sustainable construction. Clients, however, were assigned high scores across all categories, favoring indicators like ECO8 (Efficient allocation of resources), ENV3 (Eco-efficiency), and SOC8 (Human rights).

*Table 2: Pool of sustainable PM indicators for construction projects of environmental sustainability*

| Indicator | RII | Ranking by category | Overall ranking | Importance level |
|---|---|---|---|---|
| ENV1: Energy efficiency | 0.880 | 3 | 3 | H |
| ENV2: Available - fitting renewable energy resources/fossil fuels | 0.855 | 8 | 13 | H |
| ENV3: Eco-efficiency | 0.885 | 2 | 2 | H |
| ENV4: Consistent and predictable load | 0.721 | 18 | 75 | H-M |
| ENV5: Sustainable use of natural resources | 0.901 | 1 | 1 | H |
| ENV6: Up-to-date environmental construction technologies and methods | 0.872 | 5 | 6 | H |
| ENV7: Environmental responsibility/justice | 0.862 | 7 | 11 | H |
| ENV8: Construction water quality impact | 0.823 | 12 | 29 | H |
| ENV9: Environmental impact assessment project report | 0.875 | 4 | 4 | H |
| ENV10: Environmental management systems/policy implications | 0.854 | 9 | 15 | H |
| ENV11: Identify and address choke points | 0.735 | 17 | 73 | H-M |
| ENV12: Climate change adaptation/disaster risk management | 0.803 | 15 | 39 | H |
| ENV13: Appropriate and flexible environmental design details and specifications | 0.840 | 10 | 22 | H |
| ENV14: Project biodiversity | 0.815 | 14 | 34 | H |
| ENV15: Environmental education and training | 0.869 | 6 | 9 | H |

| | | | | |
|---|---|---|---|---|
| ENV16: Sustainable project delivery through project stakeholder management | 0.795 | 16 | 45 | H-M |
| ENV17: Considering the life cycle of products | 0.834 | 11 | 24 | H |
| ENV18: Environmental management plan for impacts by the PMT | 0.817 | 13 | 33 | H |

Table 2 showcases the four highest-ranked indicators, all environmental: "ENV5: Sustainable use of natural resources," "ENV3: Eco-efficiency," "ENV1: Energy efficiency," and "ENV9: Environmental impact assessment project report." These were considered crucial for achieving sustainable construction, aligning with (Ding, 2008) emphasis on environmental considerations in project success. Respondents' strong agreement with this view suggests their environmental concerns and proactive management strategies.

Spearman's Rank Correlation Coefficient ($r_s$) was used to analyze correlation coefficients between stakeholder categories. This non-parametric measure assesses the strength and direction of relationships between two variables (ranks). It ranges from +1 (perfect positive correlation) to -1 (perfect negative correlation). Equation 2 was used to calculate Spearman's ($r_s$).

$$r_s = 1 - \frac{6\Sigma d_i^2}{n(n^2-1)} \quad (2)$$

- $d_i$ is the difference between ranks assigned to variables
- n is the number of variables

*Table 3: Pool of sustainable PM indicators for construction projects of social/management sustainability*

| Indicator | RII | Ranking by category | Overall ranking | Importance level |
|---|---|---|---|---|
| SOC1: Social responsibility | 0.812 | 9 | 36 | H |
| SOC2: Social action funding/Concepts of social justice | 0.738 | 31 | 72 | H-M |
| SOC3: Corporate sustainability and organizational culture | 0.796 | 14 | 44 | H-M |
| SOC4: Labor practices | 0.812 | 8 | 35 | H |
| SOC5: Needs assessment of society/people | 0.788 | 17 | 48 | H-M |
| SOC6: Sustainable employment | 0.828 | 4 | 25 | H |
| SOC7: Community relationships and involvement | 0.776 | 22 | 55 | H-M |
| SOC8: Human rights | 0.843 | 2 | 21 | H |
| SOC9: Employee commitment/commitment in the workplace | 0.799 | 12 | 42 | H-M |
| SOC10: Public acceptance of the project | 0.823 | 6 | 28 | H |
| SOC11: Stakeholder engagement/management | 0.809 | 10 | 37 | H |
| SOC12: Project independence of political factors | 0.734 | 32 | 74 | H-M |
| SOC13: Social impact reports | 0.761 | 26 | 65 | H-M |
| SOC14: Transparent and competitive procurement processes | 0.784 | 19 | 50 | H-M |
| SOC15: Absence of bureaucracy in the workplace | 0.789 | 16 | 47 | H-M |
| SOC16: Contractor - supplier relationship | 0.786 | 18 | 49 | H-M |

| | | | | |
|---|---|---|---|---|
| SOC17: Commitment to the stakeholders' needs | 0.777 | 21 | 54 | H-M |
| SOC18: Well-defined project scope and project limitations | 0.848 | 1 | 17 | H |
| SOC19: Holistic view of benefits | 0.840 | 3 | 23 | H |
| SOC20: Product - service systems | 0.771 | 23 | 59 | H-M |
| SOC21: Emphasis on high-quality workmanship | 0.790 | 15 | 46 | H-M |
| SOC22: Encourage competition | 0.651 | 36 | 81 | H-M |
| SOC23: Implementing a quality management system | 0.807 | 11 | 38 | H |
| SOC24: First mover advantage | 0.645 | 37 | 82 | H-M |
| SOC25: Culture of accountability | 0.751 | 28 | 69 | H-M |
| SOC26: Comprehensive contract documentation | 0.757 | 27 | 66 | H-M |
| SOC27: Diversification | 0.741 | 29 | 70 | H-M |
| SOC28: Competitive tendering/comprehensive pre-tender investigation on project | 0.712 | 34 | 77 | H-M |
| SOC29: Adaptability in project environment | 0.826 | 5 | 27 | H |
| SOC30: Intangible asset management | 0.714 | 33 | 76 | H-M |
| SOC31: Multidisciplinary /competent PMT | 0.707 | 35 | 79 | H-M |
| SOC32: The role of trust within the PMT | 0.765 | 25 | 62 | H-M |
| SOC33: Following project management phases/processes | 0.781 | 20 | 52 | H-M |
| SOC34: Project manager's leadership style | 0.799 | 12 | 42 | H-M |
| SOC35: Employing of operational decision-making techniques by the PMT | 0.741 | 29 | 70 | H-M |
| SOC36: Project monitoring and evaluation by the PMT | 0.766 | 24 | 60 | H-M |
| SOC37: Managing knowledge and awareness to promote sustainable project | 0.817 | 7 | 32 | H |

# 6. Results and discussion

## 6.1. Key Sustainable PM Indicators

The study identified the most significant sustainable PM indicators for constructing sustainable buildings (Tables 1, 2, and 3). These top-ranked indicators, all receiving "High" or "High-Medium" importance (RII scores: 0.802-0.901), spanned all TBL dimensions:

1. ENV5: Sustainable use of natural resources
2. ENV3: Eco-efficiency
3. ENV1: Energy efficiency
4. ENV9: Environmental impact assessment project report
5. ECO8: Efficient allocation of resources
6. ENV6: Up-to-date environmental construction technologies and methods
7. ECO1: Financial/Economic performance
8. ECO13: Cost management plan

9. ENV15: Environmental education and training

10. ECO21: Environmental/economics accounting

These findings align with previous research emphasizing environmental and economic considerations for sustainability. However, the social aspect received the least emphasis, suggesting a need for greater focus on its practical application in project management (Geissdoerfer et al., 2017). The results confirmed environmental concerns as a top priority for most respondents. Six of the ten top indicators were environmental, reflecting the growing importance of "green" operations in sustainable construction. This aligns with research highlighting the crucial role of sustainable resource usage (Cioca and Schuszter, 2022).

## 6.2. Stakeholder Group Analysis

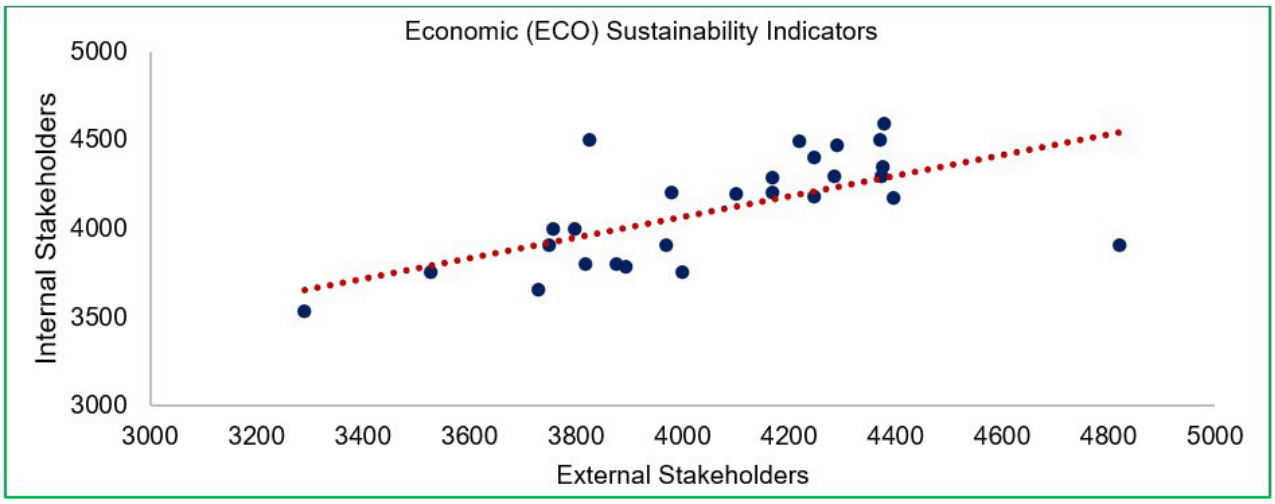
The study examined the importance of these indicators for different stakeholder groups:

- Designers/Consultants: Emphasized social/management aspects, particularly "SOC18: Well-defined project scope and limitations". This aligns with the focus on social considerations in Northern Europe (Fatourehchi and Zarghami, 2020).
- Research Academics: Prioritized environmental indicators, reflecting the influence of recent "green" policies in Europe (Wagner, 2015).
- Users: Indicators related to a human-centered approach, prioritizing social and environmental aspects.
- Manufacturers and Contractors: Focused on economic indicators, with some variations based on continent. Stakeholders in Asia and Africa prioritized economic performance due to higher political and economic risks (Al-Shboul et al., 2020).
- Government Authorities: Emphasized economic efficiency, marketing benefits, and waste recovery. This aligns with rapid urbanization and environmental protection efforts in Asia (Waris et al., 2014).
- Clients: Primarily concerned with environmental and economic indicators, with a slight emphasis on "SOC9: Employee commitment" in southern Europe.

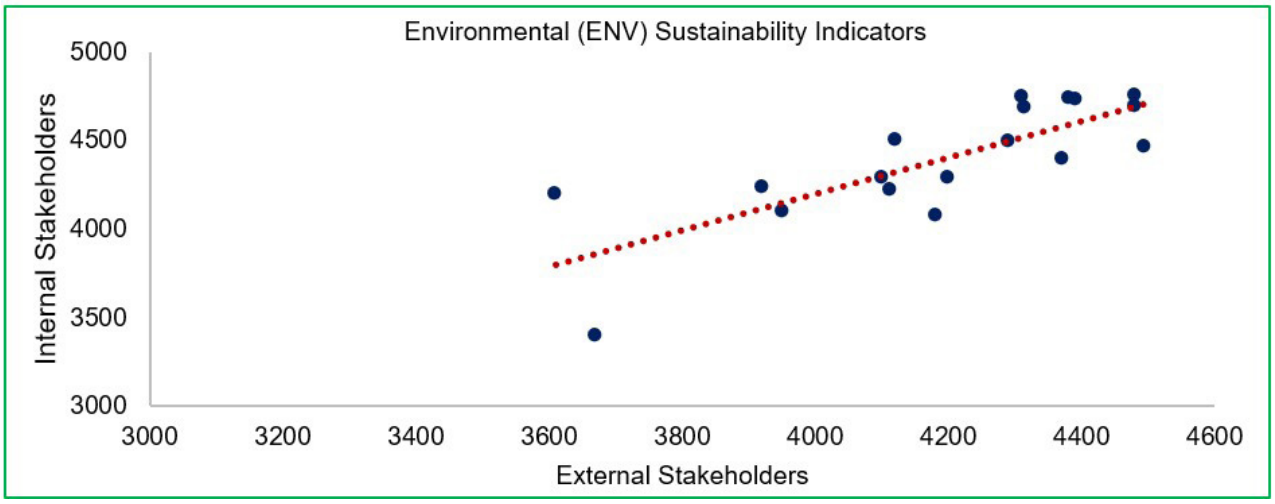
Despite prioritizing specific aspects, all stakeholder groups acknowledged the importance of all TBL dimensions for sustainable construction. Manufacturers and contractors showed the least environmental concern, likely due to their focus on economic viability within project constraints. Respondents' comments highlighted the need for a standardized strategy for implementing sustainability in construction projects. Spearman's Rank Correlation Coefficient was used to assess correlations between stakeholder categories (internal vs. external). The results in Tables 4, 5, and 6 indicated a positive to strong correlation across all TBL categories (Economic: 0.685, Environmental: 0.845, Social/management: 0.771), suggesting agreement between internal and external stakeholders and reinforcing the validity of the findings. This underscores the importance of considering stakeholder priorities for sustainable construction projects. Different groups emphasize different TBL dimensions, necessitating a holistic approach that integrates all aspects for sustainable construction (Figure 4).

*Table 4: Spearman's Rank Correlation Coefficients among Stakeholders for Economic sustainability indicators*

| Economic (ECO) sustainability indicators | Stakeholder category | | | |
|---|---|---|---|---|
| | Internal | | External | |
| | Avg. RII | Overall rank | Avg. RII | Overall rank |
| ECO1: Financial/Economic performance | 4.373 | 8 | 4.363 | 17 |
| ECO2: Economic and Political Stability | 4.098 | 34 | 4.163 | 41 |
| ECO3: Stakeholder involvement/ participation | 4.274 | 17 | 4.309 | 24 |
| ECO4: Innovation management/new product development | 4.217 | 21 | 4.462 | 12 |
| ECO5: Target marketing and benefits | 3.843 | 57 | 3.818 | 69 |
| ECO6: Effective Project Control | 4.372 | 9 | 4.327 | 22 |
| ECO7: Best practice strategy | 4.277 | 16 | 4.436 | 13 |
| ECO8: Efficient allocation of resources | 4.362 | 11 | 4.472 | 10 |
| ECO9: Customer-relationship management/ Access to a range of customers | 3.735 | 70 | 3.690 | 76 |
| ECO10: Scope control through managing changes | 3.882 | 54 | 3.818 | 69 |
| ECO11: Business ethics | 3.901 | 52 | 3.763 | 72 |
| ECO12: Facility management technologies/ general improvements | 3.970 | 46 | 3.890 | 64 |
| ECO13: Cost management plan | 4.392 | 5 | 4.145 | 43 |
| ECO14: Resource planning | 4.254 | 19 | 4.166 | 38 |
| ECO15: Supply chain collaboration | 3.772 | 67 | 3.981 | 55 |
| ECO16: Effective strategic planning | 4.166 | 27 | 4.236 | 29 |
| ECO17: Organizational culture | 3.803 | 60 | 3.981 | 55 |
| ECO18: Project outputs emphasis | 4.001 | 41 | 3.763 | 72 |
| ECO19: Developing efficient "iron triangle" parameters by the Project Management Team | 4.911 | 1 | 3.865 | 67 |
| ECO20: Ability to pay and affordability | 4.254 | 19 | 4.400 | 16 |
| ECO21: Environmental/economics accounting | 4.376 | 7 | 4.563 | 7 |
| ECO22: Developing an efficient risk management plan by the PMT | 3.980 | 45 | 4.181 | 36 |
| ECO23: Implementing an effective change management strategy | 3.850 | 56 | 4.472 | 10 |
| ECO24: Efficient data processing for decision-making practices | 4.168 | 26 | 4.181 | 36 |
| ECO25: Bureaucratic streamlining | 3.764 | 68 | 3.890 | 64 |
| ECO26: Internationalization | 3.519 | 77 | 3.745 | 75 |
| ECO27: Targeted incentives | 3.284 | 81 | 3.545 | 78 |
| Spearman's Rank Correlation Coefficient ($r_s$) | | | | |
| 0.685 | | | | |




*(a)*

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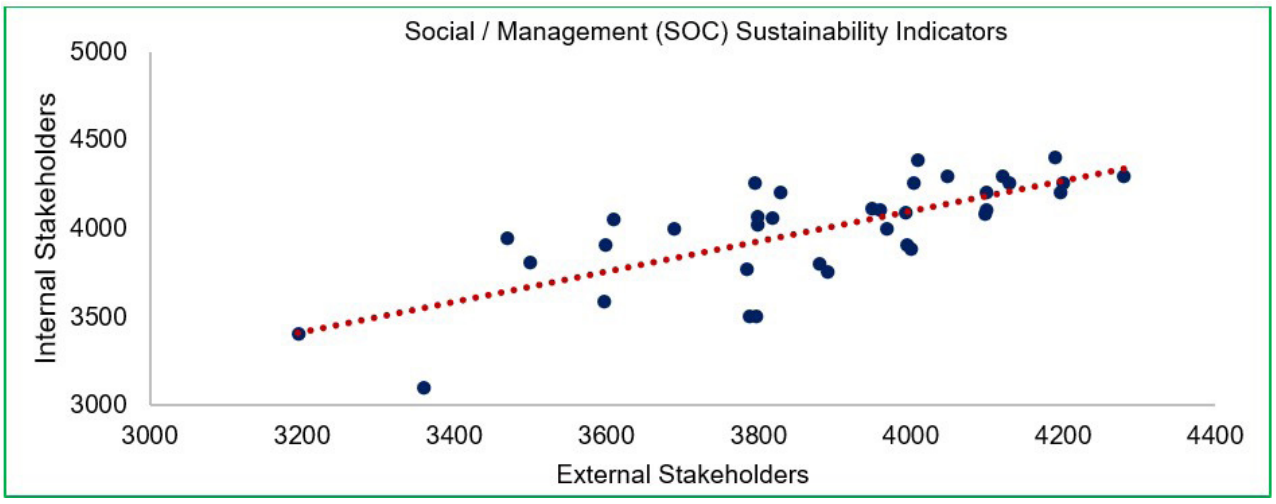


*(c)*

*Figure 4: (a) Economic, (b) Environmental, and (c) Social/Management sustainability indicators; RII views between the two major stakeholder groups*

*Table 5: Spearman's Rank Correlation Coefficients among Stakeholders for Environmental sustainability indicators*

| Environmental (ENV) sustainability indicators | Stakeholder category | | | |
|---|---|---|---|---|
| | Internal | | External | |
| | Avg. RII | Overall rank | Avg. RII | Overall rank |
| ENV1: Energy efficiency | 4.490 | 2 | 4.418 | 14 |
| ENV2: Available - fitting renewable energy resources/fossil fuels | 4.362 | 11 | 4.363 | 17 |
| ENV3: Eco-efficiency | 4.481 | 3 | 4.654 | 4 |
| ENV4: Consistent and predictable load | 3.666 | 72 | 3.345 | 81 |
| ENV5: Sustainable use of natural resources | 4.480 | 4 | 4.745 | 1 |
| ENV6: Up-to-date environmental construction technologies and methods | 4.323 | 14 | 4.709 | 2 |
| ENV7: Environmental responsibility/justice | 4.326 | 13 | 4.618 | 6 |
| ENV8: Construction water quality impact | 4.166 | 27 | 4.072 | 50 |
| ENV9: Environmental impact assessment project report | 4.372 | 9 | 4.703 | 3 |
| ENV10: Environmental management systems/policy implications | 4.294 | 15 | 4.500 | 9 |
| ENV11: Identify and address choke points | 3.617 | 74 | 4.163 | 41 |
| ENV12: Climate change adaptation/disaster risk management | 3.950 | 49 | 4.109 | 44 |
| ENV13: Appropriate and flexible environmental design details and specifications | 4.118 | 30 | 4.509 | 8 |
| ENV14: Project biodiversity | 4.107 | 32 | 4.209 | 32 |
| ENV15: Environmental education and training | 4.382 | 6 | 4.648 | 5 |
| ENV16: Sustainable project delivery through project stakeholder management | 3.931 | 51 | 4.226 | 30 |
| ENV17: Considering the life cycle of products and services to reduce environmental impacts | 4.196 | 23 | 4.301 | 25 |
| ENV18: Environmental management plan for impacts by the PMT | 4.098 | 34 | 4.296 | 26 |
| Spearman's Rank Correlation Coefficient ($r_s$) | | | | |
| 0.845 | | | | |

# 7. Conclusion and recommendations

The purpose of this research is to investigate and prioritize sustainable project management indicators that contribute to construction projects from the perspective of all stakeholders involved. The study demonstrates the creation of a comprehensive set of sustainable PM indicators for construction projects, identifying a total of 82 indicators through an extensive literature review. By using relative index analysis, the researchers evaluated the relative importance of each indicator. Through this analysis, it was determined that all indicators were of high or high-medium importance, with 42 indicators being classified as highly important. Environmental-related indicators were ranked the highest overall, as agreed upon by the respondents, indicating their significance in sustainable construction projects.

The findings of this research not only add to the existing body of knowledge on sustainable project management practices in the construction industry but also address a gap in understanding the key indicators that drive sustainable projects. The study further expands on the concept of sustainable construction by presenting a comprehensive list of sustainability indicators. These results provide stakeholders with valuable insights into the most significant indicators that impact project progress and enable them to take action accordingly, thus promoting sustainable construction practices. Moreover, the research sheds light on stakeholders' preferences for sustainable project management indicators, which can help practitioners effectively allocate roles to key stakeholders, enhancing their ability to contribute to sustainable project outcomes.

After analysing the results of the questionnaire survey, we have identified several valuable recommendations for advancing sustainable development strategies in construction projects. Firstly, governments should consider adopting more incentive-based policies that prioritize environmental protection. Secondly, the creation of socially sustainable communities should be tailored to the unique needs of each society. Thirdly, implementing existing PM strategies can greatly contribute to achieving sustainability goals. Fourthly, a deeper understanding is required regarding the allocation of credits for environmentally sustainable construction. Lastly, fostering communication between stakeholder groups is vital in promoting social ethics and maximizing contributions to sustainable development.

*Table 6: Spearman's Rank Correlation Coefficients among Stakeholders for Social/Management sustainability indicators*

| Social/Management (SOC) sustainability indicators | Stakeholder category | | | |
|---|---|---|---|---|
| | Internal | | External | |
| | Avg. RII | Overall rank | Avg. RII | Overall rank |
| SOC1: Social responsibility | 4.098 | 34 | 4.166 | 38 |
| SOC2: Social action funding/Concepts of social justice | 3.686 | 71 | 3.960 | 59 |
| SOC3: Corporate sustainability and organizational culture | 4.002 | 40 | 4.203 | 34 |
| SOC4: Labor practices | 4.094 | 37 | 4.074 | 47 |
| SOC5: Needs assessment of society/people | 3.990 | 43 | 4.073 | 49 |
| SOC6: Sustainable employment | 4.188 | 24 | 4.203 | 34 |
| SOC7: Community relationships and involvement | 3.843 | 57 | 4.166 | 38 |
| SOC8: Human rights | 4.205 | 22 | 4.296 | 26 |
| SOC9: Employee commitment/commitment in the workplace | 3.970 | 46 | 4.204 | 33 |
| SOC10: Public acceptance of the project | 4.117 | 31 | 4.333 | 20 |
| SOC11: Stakeholder engagement/management | 4.009 | 39 | 4.351 | 19 |
| SOC12: Project independence of political factors | 3.774 | 65 | 3.471 | 79 |
| SOC13: Social impact reports | 3.803 | 60 | 4.018 | 54 |
| SOC14: Transparent and competitive procurement processes | 3.960 | 48 | 3.981 | 55 |
| SOC15: Absence of bureaucracy in the workplace | 3.950 | 49 | 4.092 | 46 |
| SOC16: Contractor - supplier relationship | 3.774 | 65 | 4.222 | 31 |
| SOC17: Commitment to the stakeholders 'needs | 3.803 | 60 | 4.037 | 53 |
| SOC18: Well-defined project scope and project limitations | 4.267 | 18 | 4.333 | 20 |
| SOC19: Holistic view of benefits | 4.180 | 25 | 4.407 | 15 |

| | | | | |
|---|---|---|---|---|
| SOC20: Product - service systems | 3.830 | 59 | 4.055 | 52 |
| SOC21: Emphasis on high-quality workmanship | 4.001 | 41 | 3.903 | 63 |
| SOC22: Encourage competition | 3.178 | 82 | 3.396 | 80 |
| SOC23: Implementing a quality management system | 4.100 | 33 | 4.096 | 45 |
| SOC24: First mover advantage | 3.336 | 80 | 3.092 | 82 |
| SOC25: Culture of accountability | 3.762 | 69 | 3.777 | 71 |
| SOC26: Comprehensive contract documentation | 3.891 | 53 | 3.759 | 74 |
| SOC27: Diversification | 3.603 | 75 | 3.925 | 61 |
| SOC28: Competitive tendering/comprehensive pre-tender investigation on project | 3.590 | 76 | 3.592 | 77 |
| SOC29: Adaptability in project environment | 4.140 | 29 | 4.277 | 28 |
| SOC30: Intangible asset management | 3.495 | 78 | 3.870 | 66 |
| SOC31: Multidisciplinary /competent PMT | 3.470 | 79 | 3.944 | 60 |
| SOC32: The role of trust within the PMT | 3.782 | 64 | 3.962 | 58 |
| SOC33: Following project management phases/processes | 3.881 | 55 | 3.830 | 68 |
| SOC34: Project manager's leadership style | 3.990 | 43 | 3.925 | 61 |
| SOC35: Employing of operational decision-making techniques by the PMT | 3.623 | 73 | 4.074 | 47 |
| SOC36: Project monitoring and evaluation by the PMT, through previous experiences | 3.792 | 63 | 4.070 | 51 |
| SOC37: Managing knowledge and awareness to promote sustainable project delivery | 4.049 | 38 | 4.314 | 23 |
| Spearman's Rank Correlation Coefficient ($r_s$) | | | | |
| 0.771 | | | | |

This study has some limitations, as some respondents may not have enough professional experience to accurately evaluate all indicators. To address this, future studies should gather more diverse data from a larger group of respondents. Additionally, combining multiple decision-analysis methods (such as PROMETHEE and AHP) can strengthen research validation and alternative ranking.

Another limitation that may warrant further research is that while the study involved respondents from all continents, a country-based study could provide more context-specific results.

Overall, the findings of this study can help improve the measurement and management of sustainable projects in construction. The indicators not only include major international sustainability metrics (TBL) but also incorporate stakeholders' views. Practitioners seeking sustainable results in construction projects can refer to these indicators for guidance.

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# COMPREHENSIVE ANALYSIS OF INTERNATIONAL BEST PRACTICES FOR MITIGATING VEHICLE-RELATED MORTALITY OF THE NORTHERN WHITE-BREASTED HEDGEHOG (ERINACEUS ROUMANICUS)

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The aim of the study is to explore possible approaches for addressing ecological challenges in urban areas and the risks associated with linear infrastructures, focusing on the northern white-breasted hedgehog as a specific case. The research seeks to examine the relationship between habitat requirements and potential threats, particularly in Hungary. The primary concern arises from the increasing danger posed to the population of northern white-breasted hedgehogs, a protected species in Hungary, due to the expanding impact of linear road structures. This has led to higher mortality rates among these animals caused by habitat fragmentation and isolation effects. An analysis of a growing city was carried out using QGis mapping techniques to identify potential hedgehog habitats and assess how road systems may be threatening them. A comprehensive survey collected data on sightings of hedgehogs, types of habitats, garden characteristics (where applicable), human activity patterns throughout each day, and frequency of transportation usage. Our findings suggest that effective urban planning and raising community awareness are crucial in mitigating risks faced by hedgehogs. Implementing measures such as creating wildlife corridors or introducing traffic calming strategies can significantly lower mortality rates among hedgehogs while aiding conservation efforts for this vulnerable species.

## 1. Introduction

The northern white-breasted hedgehog *(Erinaceus roumanicus* Barrett-Hamilton, 1900) is one of the most easily recognisable members of the domestic mammal fauna. Systematically, it belongs to the order *Erinaceomorpha* and the family *Erinaceidae,* of which it is the only native representative (Fadeeva et al., 2024) in Hungary. The northern white-breasted hedgehog is classified as a synanthropic species because it occurs in higher densities in man-made environments (Rodewald and Shustack, 2008) than in the wild (Chace and Walsh, 2006), mainly due to the fact that it has a higher food availability and lower predator abundance than in the wild (Hubert et al., 2011). Hedgehogs living in artificial, human-inhabited environments tend to become active after midnight in search of food and are mostly found in larger numbers in green areas, parks, gardens and roadsides (Müller, 2018). Factors such as access to food sources or favourable microclimatic conditions play a key role in the survival of hedgehogs, with individual animal food or food or rubbish placed on the ground being an additional source of diet (Hubert et al., 2011). Apart from the fact that these habitats are excellent for hedgehogs, the roads and fences separating the habitats pose a significant challenge for the population (Wilson and Wembridge, 2018). Although some research suggests that

hedgehogs are up to 35 % less likely to be found near roads, there are countless cases of roadkill on roads across Europe (Huijser, 1998). Transportation infrastructure can have a negative impact on ecosystems as it poses a threat to the survival of vulnerable populations and disrupts ecosystem dynamics through wildlife collisions with vehicles (Backs et al., 2017). The modification of transportation infrastructure, along with the growth and alteration of road systems, can influence the extent and nature of interactions between wildlife and roads. Therefore, ongoing observation and evaluation of distinct processes and trends are essential for developing sustainable transport solutions and preserving wildlife (Rendall et al., 2021). Since the inception of modern automobile and vehicle usage, a range of cautionary symbols have been established within international legal agreements to enhance road safety and effectiveness (Tryjanowski et al., 2021). Dynamic barriers and retention nets are designed to enhance road safety and safeguard wildlife, especially in areas with elevated risk levels (Yavartanoo et al., 2023). The spatial and temporal analysis will enable the development of more focused road safety measures by identifying these high-risk areas (Steiner et al., 2014). Recognising the seasonal patterns of animal accidents may lead to reinforcing existing measures, using temporary warning signs, and implementing short-term road closures in specific areas (Grilo et al., 2020). The reduction of animal deaths from vehicle collisions with wildlife can be achieved through active or passive measures. Currently, a common approach involves blocking linear infrastructure elements to restrict wildlife access to vehicles (Pagany, 2020). The overall finding suggests that drivers can prevent collisions with wildlife by detecting animals in advance, using warning signs or animal detection systems (Huijser et al., 2006). The visibility of vehicles is an important factor for humans, but its role as a deterrent for animals is sometimes minimal (Ulrich et al., 2014). In an urban setting, the increasing use of e-mobility vehicles could have a negative impact on urban ecology. A proposal has been made to incorporate an automated vehicle intervention system, especially for autonomous vehicles, in addition to warning drivers (Viani et al., 2016). Wild animals can become accustomed to warning signals when they are not consistently followed by positive or negative reinforcement (Gilsdorf et al., 2002). Choosing the right technology for the northern white-breasted hedgehog is challenging, especially given its size.

As the world is urbanising at an ever-faster pace, cities are not only serving as places to meet people's needs but also as important habitats for the creatures around us. Recently, the loss and fragmentation of natural habitats have forced wildlife species to settle in urban areas (Smith et al., 2014). For this reason, finding the optimal way for people and wildlife to live together in harmony will be of paramount importance in the future (Magle et al., 2019), not only for the functioning of ecosystems (Cohn, 2005) but also for human mental health. The population's positive or negative attitudes and decisions have a wide range of social, psychological, and ecological consequences (Bramley et al., 2009; Cook et al., 2012).

People generally have positive attitudes towards hedgehogs. According to the survey of Kontsiotis et al. (2023) most participant expressed a willingness to financially support hedgehog conservation. In Hungary, the creation of "hedgehog-friendly gardens" is a widely applied program. This is an exceptionally important initiative, as hedgehogs are increasingly found in and around urban areas (Parrott et al., 2014; Pettett et al., 2017; van de Poel et al., 2015), and gardens associated with properties are considered favourable habitats (Dowding et al., 2010; Pettett et al., 2017). Cities, as heterogeneous ecosystems, possess complex ecological characteristics and processes (Band et al., 2005). Human activities directly and indirectly influence the ecological features of urban areas and habitats by altering both ecosystem components and abiotic and biotic infrastructure elements (Cook et al., 2012).

Although the northern, white-breasted hedgehog is widespread in Hungary and frequently reported as a roadkill (Borza et al., 2021), there are few published studies on its population size and distribution. This species is not part of the regular mammal monitoring within the Hungarian Biodiversity Monitoring System (Csorba and Pecsenye, 1997) but it is included in a popular citizen science data collection program in Hungary (vadonleso.hu). More than 1700 hedgehog observations have been contributed by civilians through this website.

The main goal of this study is to examine how the ecological requirements of the northern white-breasted hedgehog are fulfilled in typical urban and suburban areas, as well as to devise a method for evaluating the impact of roads. Győr, chosen as an example due to its high level of urbanization, was used for this investigation. A map of the city and its surrounding suburban areas was created using QGIS (2023) to identify potential habitat locations and road systems that separate them. Additionally, a questionnaire survey was conducted to assess the frequency with which citizens observe hedgehogs and explore links between observation frequency and housing area type movement habits (modes and timings).

# 2. Materials and methods

Our research focuses on a regional scale. Therefore, an example city, Győr, was chosen to demonstrate our methods. Győr is a developing industrial city situated in the northwestern part of the Transdanubian Region in the most densely populated county of Hungary. In our study, the geographic information system QGIS 3.36.3 was utilised to create map assessments and display areas where roads threaten the habitats of the northern white-breasted hedgehog. Version 3.36.3 of QGIS offers various beneficial features that have allowed us to efficiently process and analyse data with accuracy. Our work was initiated by using a map from the CORINE Land Cover database (EEA, 2020), which was then integrated with specific map data from the Geofabric database. All types of land cover suitable for hedgehogs were chosen, and roads intersecting those habitats were identified.

Our questionnaire survey included 31 different factors such as demographics, transportation methods, times of activity, housing details (such as type, yard size, fencing types and pets), and observations of hedgehogs and other migrating mammals. The timing of the questionnaire launch was adjusted to align with the annual activity patterns of the target species (in May 2024). A total of 138 respondents completed the questionnaires online while maintaining anonymity (78 were from Győr's agglomerate). The responses underwent statistical analysis using both the complete data set and a filtered dataset specific to our geographical region of interest. Contingency tables were gathered to test all relevant factors using chi-square tests and Fisher's exact test, while Spearman rank tests were used for ordinal parameter pairs in order to identify correlations among these parameters.

# 3. Results

## 3.1. Potential risk areas for linear road infrastructure of Győr

The ultimate map (Figure 1) assesses the risks associated with the local transportation infrastructure and its intersection with green spaces in the city of Győr. It takes into account primary, secondary, and tertiary roads, as well as intersections between these roads and green areas to identify potential hazard zones. Based on this foundation, various potentially hazardous areas that may be impacted by hedgehogs could be recognised.

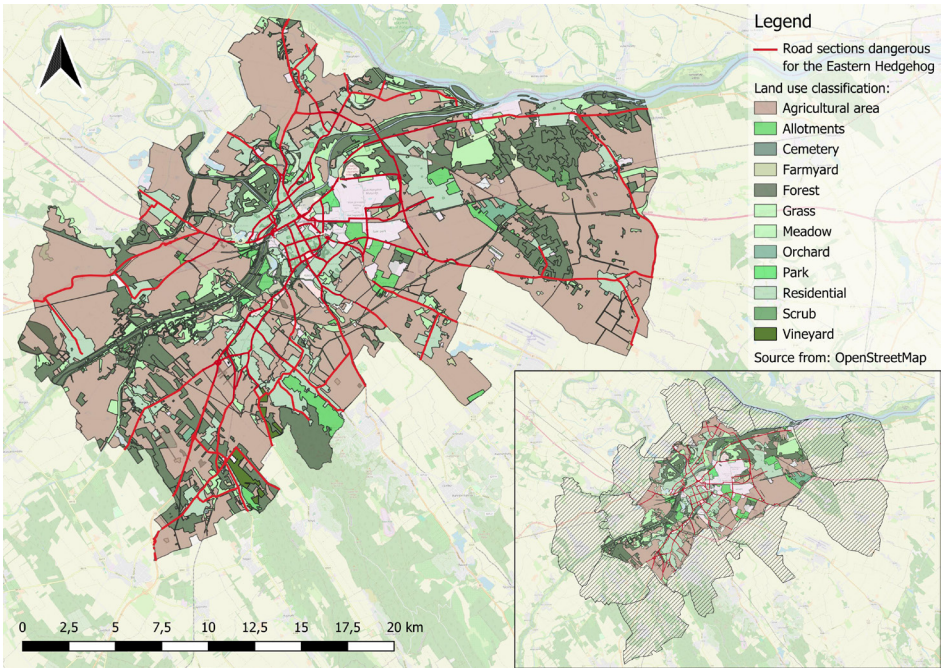


*Figure 1: Hedgehog habitat map of Győr and its agglomerate with emphasis on roads that may pose the greatest risk to these habitats*

## 3.2. Observation Questionnaire

The overwhelming majority of respondents (98.6 %) reported that they had seen a hedgehog in the wild on multiple occasions. Additional free notes definitely reflect a positive attitude toward the species.

Responses to the matrix question "How often do you drive a car/travel as a passenger in a car /use public transport /ride a bike or scooter/ walk more than 500 m?" on a six-point scale from never to daily were combined with "Have you ever seen a hedgehog alive along a road/ carcass on the road?" on a 5-point scale from never to more than 4 times questions. For all pairs of parameters, contingency tables and Spearman rank test was performed. Calculated p-values are shown in Table 1. The results suggest no significant correlation among most parameters. Particularly, biking more often shows the least connection to observing more hedgehogs, either alive or dead. However, we observed a significant correlation between the frequency of walking and spotting live hedgehogs along roads. A near 0.05 p-value between the regularity of using public transport and observing live hedgehogs on the road can be explained by the significant correlation between the usage of public transport and walking.

*Table 1: The p-values of Spearman rank test about correlations among travelling behaviour and observations of hedgehogs along roads*

| | Driver | Passenger | Public transport | Biking | Walking |
|---|---|---|---|---|---|
| Alive on road | 0.4240 | 0.1011 | 0.0547 | 0.8974 | 0.0409 |
| Carcass on road | 0.1437 | 0.5233 | 0.7543 | 0.9278 | 0.6277 |

Answers to the matrix question "How frequently do you spend time outdoors at specific times of the day?" were collected using a five-point scale ranging from rarely to daily for 8 time intervals and compared to the matrix question "How often have you seen hedgehogs [location]?". The p-values obtained from Spearman rank tests are presented in Table 2. The strongest association between outdoor presence and responses was observed during late night hours, while extremely high p-values in periods 8-12 and 15-17 indicate a lack of correlations.

*Table 2: The p-values of the Spearman rank test about correlations among periods of daily activity outside and observations of hedgehogs in different places*

| Locations \ time (h) | 4-6 | 6-8 | 8-12 | 12-15 | 15-17 | 17-20 | 20-22 | 22-4 |
|---|---|---|---|---|---|---|---|---|
| Alive on road | 0.0082 | 0.5624 | 0.7059 | 0.0805 | 0.7579 | 0.5490 | 0.0019 | 0.0004 |
| Carcass on road | 0.5569 | 0.1677 | 0.5404 | 0.0054 | 0.6760 | 0.5490 | 0.2299 | 0.8577 |
| In own yard | 0.6948 | 0.0993 | 0.2532 | 0.6353 | 0.4122 | 0.5635 | 0.2321 | 0.7768 |
| In others' yard | 0.1705 | 0.5483 | 0.7899 | 0.4113 | 0.8958 | 0.5628 | 0.5814 | 0.0703 |
| In green area in town | 0.1294 | 0.2873 | 0.6999 | 0.0434 | 0.6299 | 0.2086 | 0.0370 | 0.0014 |
| In green area outskirts | 0.1455 | 0.0579 | 0.6238 | 0.1926 | 0.3612 | 0.9050 | 0.5438 | 0.0068 |

In case of "What the size of the green area (grass, bushes) inside your yard?" contra "How often have you seen hedgehogs [in your own yard]?" the Spearman rank test revealed no significant correlation ($p=0.1244$), despite some association observable in the graphical representation (Figure 2A). When the number of categories for yard size was reduced to "under and over 301 m²" a significant but moderate positive association was found using Kendall's tau test ($p=0.03$, $\tau=0.2259$).

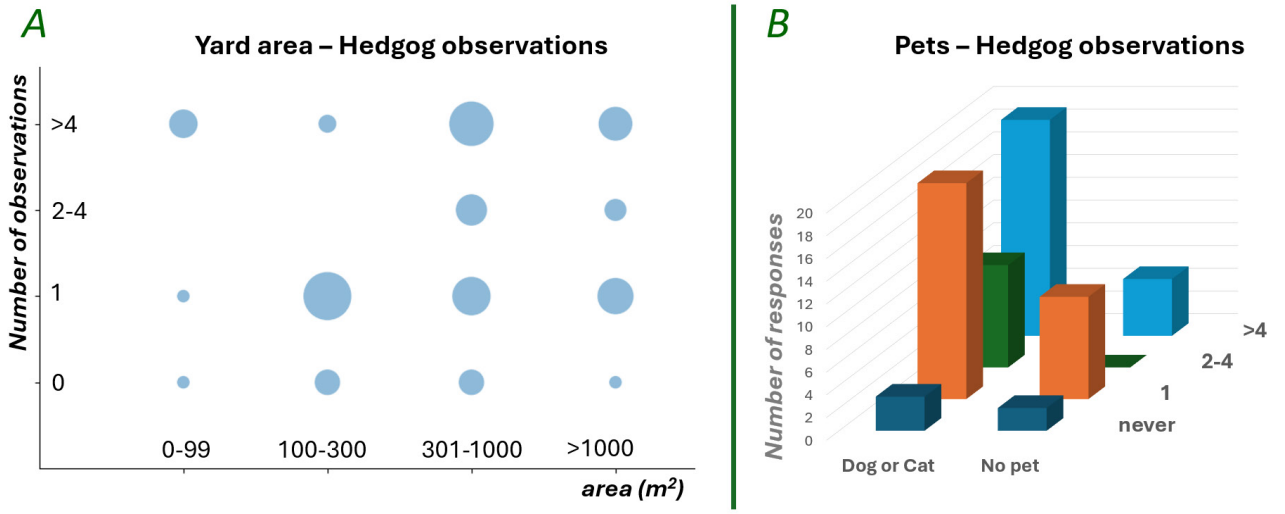


*Figure 2: A) Correlation between the green area in the enclosed yard and the number of hedgehog observations. Bubble sizes represent the number of respondents with a specific combination of answers (filtered to Győr agglomerate and having a fenced garden). B) Relationship between having a pet in one's own yard and the number of hedgehog observations*

Based on responses to "What kind of pets do you keep in your yard?" and "How often have you seen hedgehogs [in your own yard]?", there was no significant correlation found for having a cat (p=0.312) or a dog (p=0.255). Since a considerable number of respondents have both cats and dogs, a chi-square test was also calculated for the combined categories of "having a cat or dog" versus "no cat or dog" (p=0.198) (Figure 2B).

As there were no respondents who have never seen a hedgehog or any other mammal larger than a hedgehog and have only fence types that are impermeable to hedgehogs, it can be inferred that the fences in the region are generally permeable to hedgehogs.

# 4. Conclusions

Our questionnaire results are in accordance with the former data, which shows that the northern white-breasted hedgehog is widely common. Generally, there are significant connections among observational parameters (seeing hedgehogs as carcasses on the roads/ alive on roads/in their own yards/ in others' yards/ in open green areas within the settlement / outside the settlement). This suggests that some people may be more observant or that seeing hedgehogs multiple times can make it difficult to remember where they were seen. Hedgehogs are more often observed in larger yards. However, a further increase in yard size over 300 $m^2$ has no additional positive effect. In accordance with hedgehogs' activity patterns, human outdoor activity in the late night and early morning is significantly correlated with hedgehog observations. Keeping cats and dogs has no significant effect on hedgehog occurrence. The permeability of common fence structures allows hedgehogs to use yards as a continuous habitat, with roads being the only considerable barriers. Consequently, mapping habitable areas and their conflict with busy roads is a reliable tool for integrating urban ecological planning at the settlement and regional levels. The positive attitude of humans toward hedgehogs could be leveraged to enhance public involvement in citizen science data collection and roadkill prevention programs.

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# IMPACT OF VRUS ON THE CAPACITY OF SINGLE-LANE ROUNDABOUTS

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This study examines the influence of Vulnerable Road Users (VRUs), specifically pedestrians and cyclists, on the entry capacity of urban single-lane roundabouts using non-linear regression modeling, with implications for sustainable urban transportation planning. Data were collected at a single-lane roundabout in Győr, Hungary, through video surveillance, capturing interactions among vehicles, pedestrians, and cyclists during peak traffic hours. The analysis demonstrated that incorporating pedestrian and cyclist volumes into the capacity models significantly improved predictive accuracy, increasing $R^2$ values from 0.5 (vehicles only) to over 0.8 in the extended models. The results indicate that pedestrian and cyclist interactions reduce entry capacity by up to 30 % and 40 %, respectively. ANOVA tests confirmed the statistical significance of these findings ($p < 0.0001$).

By providing a more precise estimation of roundabout entry capacity that accounts for the non-linear effects of VRUs, the refined model supports the development of transportation systems that prioritize sustainable mobility. These findings underscore the critical need to integrate VRUs into capacity assessments to inform design modifications that promote safe and efficient multimodal transportation. Such integration facilitates the reduction of vehicular congestion and emissions, contributing to improved air quality and urban livability, aligning with broader environmental objectives in sustainable urban development.

## 1. Introduction

Roundabouts are integral components of urban transportation systems, renowned for their ability to enhance traffic flow and safety by managing vehicle interactions to minimize congestion and accident rates (Akçelik, 2003). However, as urban areas become increasingly dense and diverse in terms of road users, traditional capacity models often fall short (Lenters and Rudy, 2010). These models typically focus on motorized vehicles and overlook the complex dynamics introduced by Vulnerable Road Users (VRUs), such as pedestrians and cyclists, leading to inefficiencies and heightened safety risks (Mallikarjuna, 2014).

Traditional linear capacity models tend to oversimplify the interactions between vehicles and VRUs, assuming direct proportionality between traffic inputs and outputs (Bahmankhah, et al., 2019). Such models fail to capture the nuanced, often non-linear effects that VRUs have on traffic dynamics, especially under variable urban traffic conditions. Internationally, significant variations exist in how VRUs are integrated into capacity models. European countries like the UK and France have adapted their models to better account for pedestrian and cyclist impacts, reflecting a broader commitment to safe and sustainable urban mobility (Akçelik and Troutbeck, 2021). These adaptations often involve non-linear approaches to accommodate irregular and dynamic interactions. Conversely, the United States has only recently begun to revise its models to include similar considerations, highlighting a global recognition of the importance of VRUs in traffic analyses (Akçelik, 2011).

Despite these advancements, existing capacity models in Hungary inadequately account for the influence of pedestrians and largely ignore cyclists (MAÚT, 2010). This oversight is increasingly problematic in urban

areas where VRU volumes are substantial. The lack of integration of VRUs into capacity models leads to potential underestimation of delays and capacity reductions (Poudel and Singleton, 2021).

From a sustainability perspective, accurate roundabout capacity modelling is pivotal for optimizing traffic flow efficiency and has a direct impact on sustainability by minimizing delays, reducing fuel consumption, and lowering emissions (Zegeer and Bushell, 2012). Technically, precise models that incorporate detailed parameters such as entry flow rates and circulating flow rates, in addition to the stochastic interactions with Vulnerable Road Users (VRUs) like pedestrians and cyclists, enable engineers to predict roundabout performance under varying traffic conditions with high fidelity. By accurately estimating capacity and accounting for non-linear relationships between traffic variables, these models help in designing roundabouts that prevent oversaturation, thereby avoiding exponential increases in queue lengths and vehicular delays as described by queuing theory and traffic flow fundamentals (Akçelik, 2011). This reduction in delays leads to smoother traffic flow, decreasing engine idling and stop-and-go conditions, which in turn reduces fuel consumption and emissions of pollutants such as $CO_2$, NO□, and particulate matter (Barth and Boriboonsomsin, 2008). Additionally, incorporating VRUs into capacity assessments ensures that the infrastructure supports non-motorized transport modes, promoting a modal shift toward walking and cycling. This shift contributes to sustainability objectives by decreasing reliance on fossil fuels, mitigating traffic congestion, and improving urban air quality (Poudenx, 2008).

By addressing these gaps, the aim of this research is to refine the existing roundabout capacity model for urban single-lane roundabouts in Hungary by integrating empirical data on VRU movements collected through extensive video surveillance at a roundabout in Győr, Hungary. The novelty of this study lies in the integration of pedestrians and cyclists into roundabout capacity estimation.

The following sections of this paper detail the methodology employed in the study, present our findings and discuss their implications for traffic management. Additionally, we explore how these findings support ongoing efforts to create sustainable urban transportation frameworks that are inclusive of all road users.

# 2. Methodology

## 2.1. Study site selection

Our study was conducted at a single-lane roundabout in Győr, Hungary. This location was selected due to its typical urban roundabout configuration with four legs, each featuring well-defined pedestrian and bicycle crossings. Such configurations are representative of many urban roundabouts across Europe, making it a relevant case study for examining the interactions among vehicles, pedestrians, and cyclists. The choice of this site ensures the generalizability of our findings to similar urban traffic environments, supporting sustainable urban mobility initiatives. The roundabout is located at 47.674462° N, 17.649212° E, which is a critical junction for traffic flow in the city. Figure 1 shows the roundabout along with the labels given to the four legs.

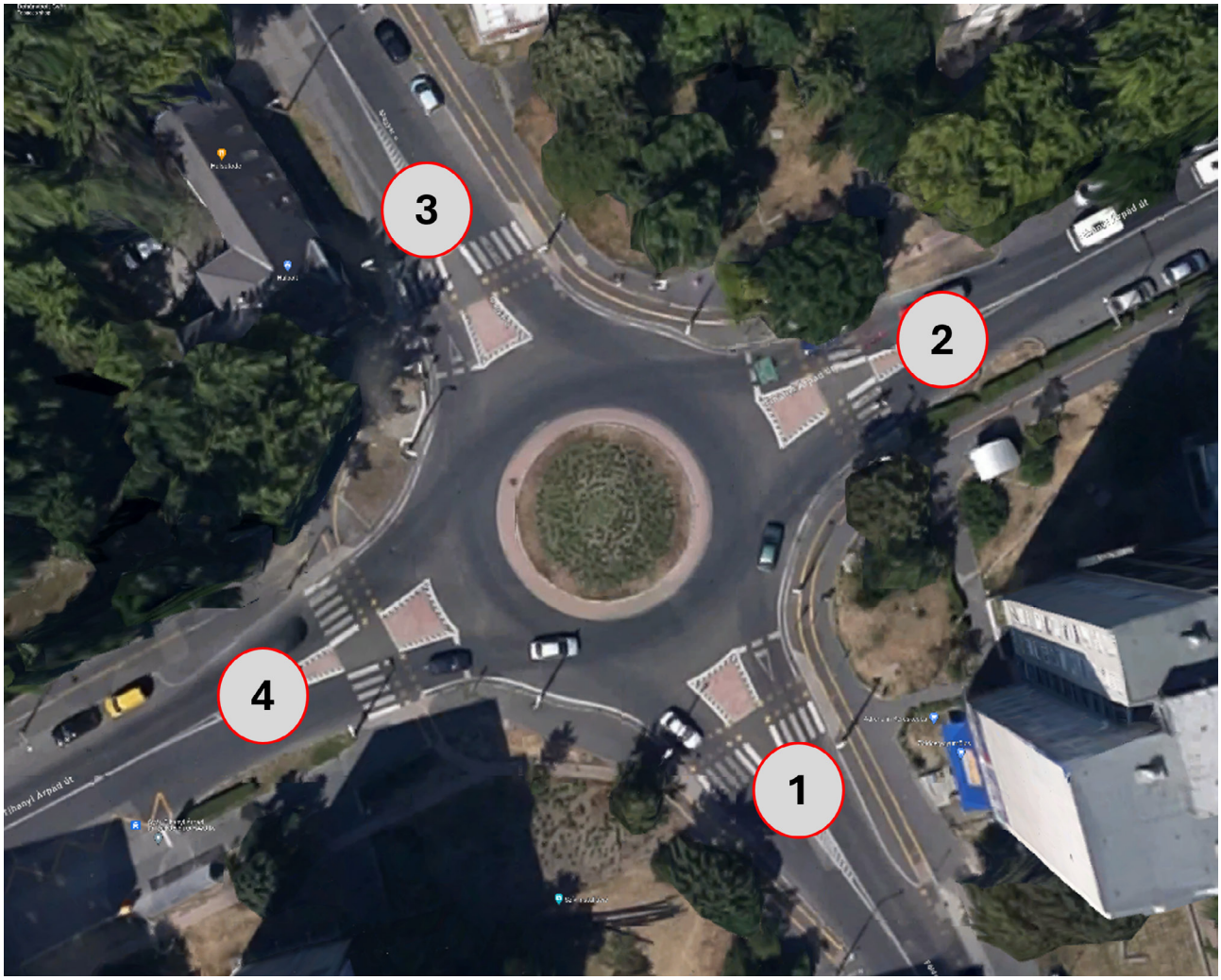


*Figure 1. Selected roundabout along with adopted labels for the four legs*

## 2.2. Data collection

Data was collected through detailed video recordings captured during peak traffic hours, specifically from 7:00 AM to 9:00 AM and from 4:00 PM to 6:00 PM, on typical clear weather working days. A total of 10 h of footage was meticulously planned to encompass a variety of traffic conditions, ensuring a comprehensive dataset for subsequent analysis. A 360-degree camera was positioned to capture all approaches of the roundabout. This extensive surveillance allows for an accurate assessment of how well current infrastructure supports VRUs, an essential factor in promoting sustainable transportation options.

## 2.3. Data analysis

The video footage was analysed in 1-minute intervals, a timeframe selected to balance granularity with manageability of data. We focused on near-capacity situations, where the interplay between traffic volume and roundabout performance is most critical. Saturated conditions in which the priority rules are violated were excluded. The initial analysis involved developing a baseline model to quantify the primary effects of circulating vehicle volume on the entry capacity of the roundabout. The model was then expanded to incorporate the additional dynamics introduced by pedestrian and bicycle flows.

The Analysis of Variance (ANOVA) test is crucial for assessing differences among three or more independent groups in this study: a baseline model (vehicles only) and extended models including pedestrians and both

pedestrians and cyclists. By applying ANOVA, we quantitatively evaluate if integrating Vulnerable Road Users (VRUs) significantly improves model fit.

### 2.4. Objectives and expected outcomes

The primary goal of this study is to refine the Hungarian roundabout capacity model, a non-linear exponential model developed by the Hungarian Road and Rail Society [30]. This model accounts for the pseudo-conflict between entering and circulating vehicles by incorporating the width of the splitter island to help manage traffic flow separation. It also considers the impact of pedestrian traffic through a reduction factor based on pedestrian rates. We aim to enhance the model's accuracy by including additional aspects such as cyclist interactions. The anticipated outcome is an improved model that not only accommodates cyclists but also applies to more varied and sustainable traffic scenarios.

## 3. Data analysis

In this study, we employed non-linear regression models to analyze the impact of circulating traffic (Qc), pedestrians (P), and cyclists (C) on entry traffic (Qe) at each roundabout leg. Each leg was analyzed under different configurations to assess how traffic composition variations affect Qe.

Initially, the base model used Qc as the sole predictor, where $\beta_0$ and $\beta_1$ are estimated parameters and formulated as:

$$Qe = \beta_0 \times e^{\beta_1 \cdot Qc} \tag{1}$$

We then expanded the model to include pedestrians, and subsequently both pedestrians and cyclists, where $\beta_2$ and $\beta_3$ measure the impacts of pedestrians and cyclists, respectively and structured as:

$$Qe = \beta_0 \times e^{\beta_1 \cdot Qc + \beta_2 \cdot P} \tag{2}$$

$$Qe = \beta_0 \times e^{\beta_1 \cdot Qc + \beta_2 \cdot P + \beta_3 \cdot C} \tag{3}$$

In the developed non-linear regression models, the parameters $\beta_1$, $\beta_2$, and $\beta_3$ represent the coefficients corresponding to circulating traffic volume (Qc), pedestrian flow (P), and bicycle flow (C), respectively. These parameters were estimated using non-linear regression by directly fitting the predefined exponential models to the 1-minute interval data of the predictive parameters Qc, P and C.

Goodness of fit was evaluated by the R-squared value, which measures how much variance in Qe is explained by the predictors (Qc, P, C), indicating the model's accuracy.

Incrementally adding these variables highlighted the substantial influence of pedestrians and cyclists on roundabout dynamics. This approach enhances our understanding of complex traffic interactions and supports targeted urban traffic planning and safety strategies by highlighting critical vehicular and non-vehicular interactions. This comprehensive approach underscores the importance of factoring in diverse traffic components in traffic models to enhance their predictive reliability and effectiveness in urban traffic management and planning. The results are summarized in the table below (Table 1).

*Table 1. Nonlinear regression results for all legs.*

| Leg | Model | Equation | $R^2$ |
|---|---|---|---|
| Leg 1 | Base Model | $Qe = 842.97 \times e^{(-0.00149 * Qc)}$ | 0.455 |
| | Extended Model 1 | $Qe = 885.23 \times e^{(-0.00088 * Qc - 0.00129 * P)}$ | 0.776 |
| | Extended Model 2 | $Qe = 907.61 \times e^{-0.00088 * Qc - 0.00121 * P - 0.00057 * C}$ | 0.778 |
| Leg 2 | Base Model | $Qe = 1217.91 \times e^{-0.00169 * Qc}$ | 0.444 |
| | Extended Model 1 | $Qe = 1210.54 \times e^{-0.00083 * Qc - 0.00193 * P}$ | 0.858 |
| | Extended Model 2 | $Qe = 1218.85 \times e^{-0.00083 * Qc - 0.00187 * P - 0.00029 * C}$ | 0.859 |
| Leg 3 | Base Model | $Qe = 934.574 \times e^{-0.0016 * Qc}$ | 0.484 |
| | Extended Model 1 | $Qe = 995.28 \times e^{-0.001159 * Qc - 0.001223 * P}$ | 0.751 |
| | Extended Model 2 | $Qe = 969.59 \times e^{-0.000976 * Qc - 0.001025 * P - 0.001267 * C}$ | 0.783 |
| Leg 4 | Base Model | $Qe = 992.6372 \times e^{-0.0018 * Qc}$ | 0.722 |
| | Extended Model 1 | $Qe = 1017.90 \times e^{-0.001465 * Qc - 0.000740 * P}$ | 0.766 |
| | Extended Model 2 | $Qe = 1042.00 \times e^{-0.001226 * Qc - 0.000565 * P - 0.001945 * C}$ | 0.814 |

Results of the regressions are displayed in plots below. First, only entry traffic versus circulating traffic. Then, entry traffic versus circulating traffic and pedestrian traffic and finally entry traffic versus circulating traffic, pedestrians, and cyclists.

## 3.1. Entry traffic vs circulating traffic

In this analysis, the non-linear regression models applied to all the legs of the roundabout reveal a clear inverse relationship between circulating and entry traffic: as circulating traffic increases, entry capacity decreases. This trend is consistently captured by the fitted models (red lines), which closely align with the observed data (blue 'X' marks). Similar patterns were observed in Legs 3 and 4.

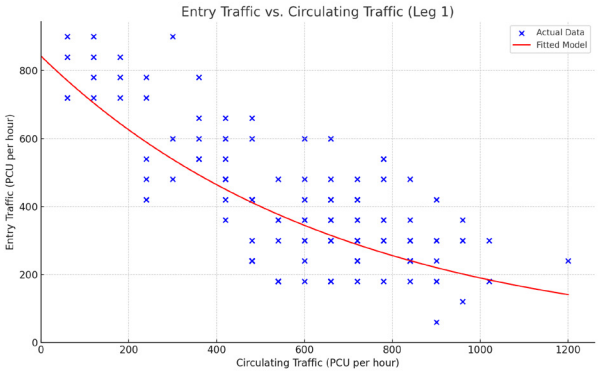


*Figure 2. Base model fitting for leg 1*

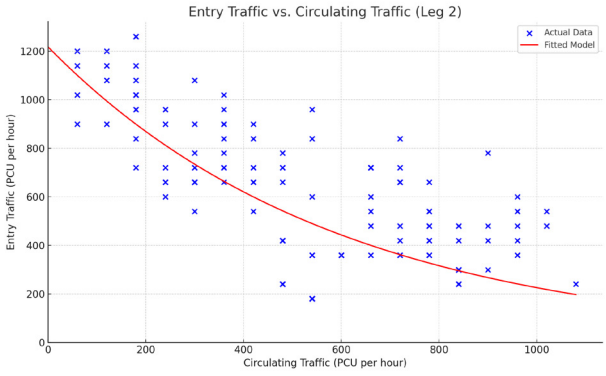


*Figure 3. Base model fitting for leg 2*

## 3.2. Entry traffic vs circulating traffic and pedestrians

In this analysis, non-linear regression models incorporate the impact of pedestrian presence, revealing that increasing pedestrian counts further decrease entry traffic capacity. Each regression line, represented by a gradient from yellow to purple, correlates with increasing ranges of pedestrian counts, demonstrating a progressive reduction in entry capacity as pedestrian volume grows. Similar impacts of pedestrians were also observed in Legs 3 and 4.

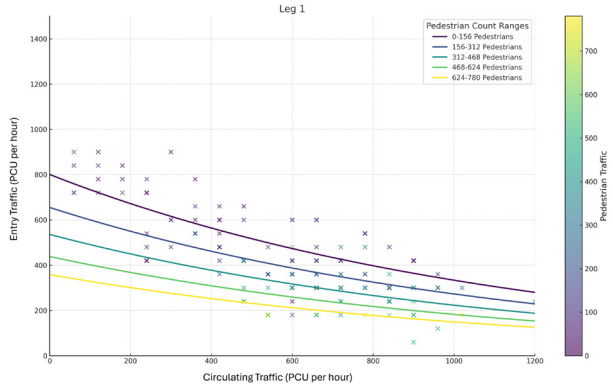


*Figure 4. Extended model 1 fitting for leg 1*

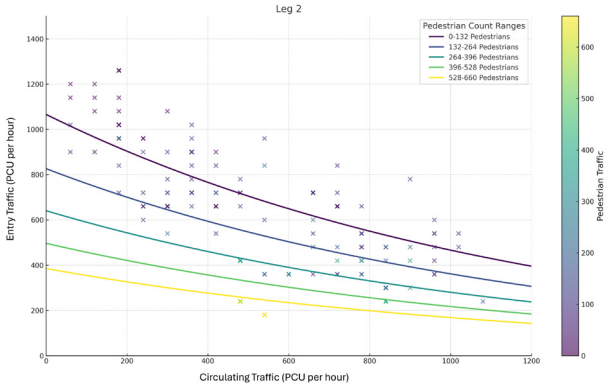


*Figure 5. Extended model 1 fitting for leg 2*

## 3.3. Entry traffic vs circulating traffic, pedestrians, and cyclists

In this further analysis, the non-linear regression models are expanded to include the effects of cyclists. The models demonstrate that as cyclist counts increase, entry traffic capacity decreases further. Each regression line, differentiated by a color gradient representing increasing cyclist counts, illustrates a more pronounced decline in entry capacity with higher cyclist volumes. Similar patterns were detected in Legs 3 and 4.

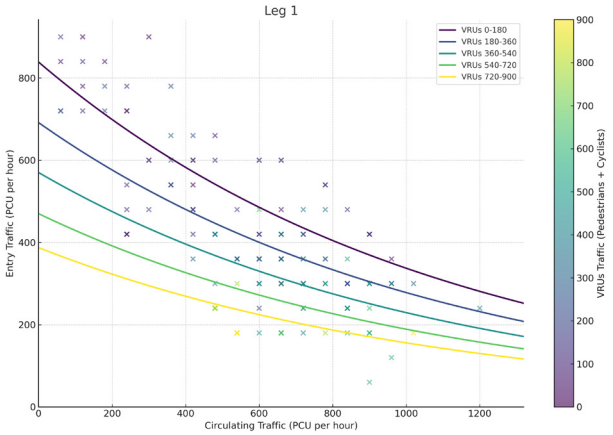


*Figure 6. Extended model 2 fitting for leg 1*

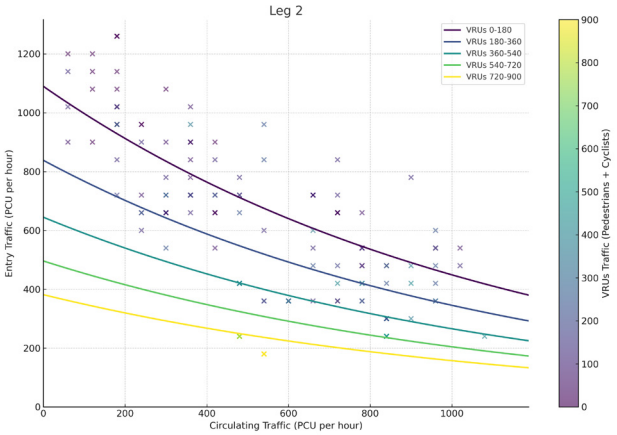


*Figure 7. Extended model 2 fitting for leg 2*

## 3.4. ANOVA comparison

The Analysis of Variance (ANOVA) test is crucial for assessing differences among three or more independent groups in this study: a baseline model (vehicles only) and extended models including pedestrians and both pedestrians and cyclists. By applying ANOVA, we quantitatively evaluate if integrating VRUs significantly improves the model fit. This is indicated by the F-statistic, which compares variance between groups to variance within groups, and the p-value, which tests if all group means are statistically similar. Significant results (low p-value and high F-statistic) confirm that adding pedestrians and cyclists enhances the model's accuracy and reliability, supporting their inclusion in traffic models to better reflect urban dynamics.

*Table 2. ANOVA test results for all legs.*

| Leg | Model Comparison | F-Statistic | p-Value | Significance |
|---|---|---|---|---|
| Leg 1 | Base vs. Ext 1 | 323.88 | <0.0001 | Yes |
| | Ext 1 vs. Ext 2 | 9.46 | 0.0024 | Yes |
| Leg 2 | Base vs. Ext 1 | 601.26 | <0.0001 | Yes |
| | Ext 1 vs. Ext 2 | 0.20 | 0.656 | No |
| Leg 3 | Base vs. Ext 1 | 299.92 | <0.0001 | Yes |
| | Ext 1 vs. Ext 2 | 29.54 | <0.0001 | Yes |
| Leg 4 | Base vs. Ext 1 | 97.00 | <0.0001 | Yes |
| | Ext 1 vs. Ext 2 | 69.71 | <0.0001 | Yes |

ANOVA tests show significant model improvements when pedestrians are included as predictors, underscoring their critical role in traffic dynamics. The addition of cyclists also significantly enhances model fit in specific legs (Leg1, Leg 3 and Leg 4), reflecting their variable impact. These findings affirm the importance of incorporating VRUs like pedestrians and cyclists into traffic models for more precise urban traffic planning predictions.

# 4. Findings

The inclusion of pedestrians and cyclists significantly enhances the accuracy of the developed model, as indicated by higher $R^2$ values. This improvement underscores the pivotal role of VRUs in traffic dynamics and validates the models' ability to mirror actual traffic behaviours more precisely.

Incorporating a broad spectrum of road users into our models aligns with urban planning strategies aimed at improving road safety and operational efficiency. This approach contributes to sustainability by promoting smoother traffic flow and reducing reliance on vehicles, thereby decreasing congestion and emissions. Further validation through ANOVA tests confirms the robustness of our findings, emphasising the critical need to integrate diverse user groups into traffic models to truly reflect the complexities of urban traffic.

This empirical evidence supports the development of traffic management strategies that not only aim for efficiency but also enhance the sustainability of urban environments. By demonstrating the tangible benefits of inclusive modeling, this study contributes to a deeper understanding of the sustainable development goals in urban planning.

# 5. Limitations & future research

This study offers valuable insights into how pedestrians and cyclists impact roundabout capacity. However, it has several limitations. Focused on circulating traffic and pedestrian and bicycle flows, the research was conducted at a single roundabout in Győr, Hungary, limiting its applicability to other urban environments with different traffic patterns. Data collection was restricted to clear weather and peak hours, potentially missing variations under adverse conditions or off-peak times. Key factors such as vehicle mix, driver behaviour, and geometric design were also excluded due to data constraints. These limitations underscore the need for future research with more comprehensive data collection methods, such as vehicle classification and behavioural observations, to improve the robustness of capacity models.

# 6. Discussion and conclusions

This study presents a refined non-linear regression model for estimating the capacity of urban single-lane roundabouts by integrating the effects of Vulnerable Road Users (VRUs), specifically pedestrians and cyclists. The inclusion of VRU flow rates as independent variables significantly enhanced the model's predictive accuracy, with $R^2$ values increasing from approximately 0.5 in the base models to over 0.8 in the extended models. The statistical significance of these improvements was confirmed through ANOVA tests ($p < 0.0001$), underscoring the substantial impact of VRUs on entry capacity. The negative coefficients associated with pedestrian and cyclist volumes indicate that higher VRU flows result in decreased entry capacities, which aligns with theoretical expectations of increased yielding behaviour and occupancy times at conflict points.

The refined model captures the non-linear and stochastic nature of traffic interactions at roundabouts, accounting for the exponential relationship between circulating flow, VRU volumes, and entry capacity. This advancement enables the prediction of delays and queue lengths with greater precision, facilitating the optimization of roundabout design elements such as entry widths, flare lengths, and splitter island dimensions to mitigate congestion and enhance operational efficiency.

The integration of VRUs into capacity modelling has significant implications for sustainable urban transportation planning. By accurately reflecting the influence of pedestrians and cyclists on roundabout performance, the refined model promotes infrastructure designs that accommodate non-motorized modes of travel, encouraging a modal shift away from private vehicles. This shift contributes to reduced vehicular emissions, lower fuel consumption, and decreased congestion, aligning with environmental sustainability objectives. Additionally, the improved modelling of VRU interactions supports the development of policies and design guidelines that prioritise inclusive mobility, ultimately leading to transportation systems that are more efficient, safe, and responsive to the diverse needs of urban populations.

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# HOW SAFE ARE LEVEL ROAD-RAILWAY CROSSINGS FOR THE MOST SUSTAINABLE TRANSPORTATION MODES: PEDESTRIANS AND CYCLISTS?

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**Relative to the volume of traffic, there are fewer accidents at level road-railway crossings than at road intersections. The better accident rates are primarily due to the strict regulation of the rail transport system. Level road-railway crossings are usually distinguished according to, among others, the safety devices used at the crossing, which primarily depends on the amount of traffic. Secured passages are most often provided with light barriers or light barriers and half barriers. At the same time, the safety systems for pedestrians and cyclists in many railway crossings fall short of that for motorised vehicles; for example, in railway crossings secured with light and half barriers, pedestrians only have a calling light signal. The barrier has sufficient deterrent force for vehicles, while pedestrians and cyclists can move more freely on the less secured facilities, which is why irregular, dangerous crossings are more likely to occur. The safety of pedestrians and cyclists, which are considered the most sustainable transportation modes, deserves more attention in the case of railway crossings as well. The aim of this paper is to examine the safety of pedestrians and cyclists at railway crossings based on a literature review, field surveys, accident data and behaviour questionnaires.**

## 1. Introduction

When two traffic routes cross, there is always a likelihood of conflict, whether at different types of road crossings or at the road-rail level crossings that are the subject of this paper. The latter, moreover, differs from road intersections in that it is a crossing between two tracks of different designs, which are subject to different rules and instructions. Consequently, the conflict is different from that at a road junction. In his thesis, Dr. Major analysed in detail the accidents that occurred at level crossings in Hungary between 2002 and 2007 and compared them with road accidents (Major, 2009). Although the number of accidents at level crossings is much lower than on the roads, the fact is that they are very serious. It is also a fact that the likelihood of fatalities is almost ten times higher than in the average accident. Level crossings can be divided into two categories: insured and uninsured. In an unprotected level crossing, the driver of a road vehicle is only informed of the crossing by a "Start of level crossing" sign, without any information about approaching railway vehicles. A secured level crossing (whether it is equipped with a full barrier, a light barrier, or a light and light barrier) will, in turn, inform not only drivers but also other road users of approaching railway vehicles and if the equipment is out of order. In addition to drivers, an unsecured crossing does not inform pedestrians or cyclists of approaching trains. In this paper, we focus on the latter two groups and how they behave when crossing level crossings. The aim of this paper is to improve safety and to raise awareness of the risks and dangers of level crossings for pedestrians and cyclists.

# 2. Literature review

The safety of level crossings, particularly for pedestrians and cyclists, is a global concern. Numerous studies highlight the importance of understanding road user behaviour and implementing safety measures to mitigate risks.

A study conducted in Hungary investigated the behaviour of pedestrians and cyclists at 14 level crossings (Lányi & Gábor, 2014). They found that while road vehicles generally adhered to crossing rules, pedestrians often violated regulations by crossing before or after the train had passed. The labyrinth guardrail was frequently avoided by pedestrians and cyclists.

Further research on the Hungarian State Railways (HSR) line 30, focusing on crossings in the Lake Balaton area, revealed a similar pattern (Vágány, 2018). Notably, the crossing on Mártírok Street in Siófok exhibited the highest rate of violations due to its visibility and proximity to the railway station.

The dangerousness of level crossings in Hungary has been assessed since 1993 by the Institute of Transport Science (ITS) (Gábor et al., 2015). This ranking, based on accident records and visibility analyses, highlights the need for comprehensive modernisation of level crossing regulations.

Studies abroad reinforce the importance of pedestrian and cyclist behaviour analysis. An Austrian-German study used a combination of infrared and conventional cameras to evaluate the impact of speed reduction thresholds on road user behaviour (Hartwig et al., 2020).

A Croatian study focused on the city of Zagreb, providing an overview of cycling characteristics and examining pedestrian and cyclist behaviour at level crossings (Pilko et al., 2014). This research aims to inform future level crossing design and road safety measures.

As for pedestrians, accidents at secured level crossings are also caused by road users (including pedestrians) trying to cross when the level crossing is closed (Kamphuis, 2021). Kamphuis highlighted the role of road user behaviour in accidents at secured level crossings, emphasising the importance of passive and active safety devices. Passive devices include raising the approach and area between tracks to the level of the rail guardrail, while active devices encompass light barriers, audible warning devices, automatic level crossings, and variable message signs. Regular inspections of high-traffic level crossings, especially those near schools or with inadequate sight distances, are crucial.

Education plays a significant role in promoting safety. A US study emphasised the need for local authorities to provide pedestrian and cyclist education to reduce accidents (Ranallo, 2013).

New Zealand guidelines incorporate human factors, promoting awareness of level crossings and appropriate traffic behaviour (Turner et al., 2021). The guidelines also propose innovative solutions like in-ground LED warnings and new crossing designs.

Cyclists in Scotland need to pay close attention to safe passage through level crossings, according to Cycle Grampian (Cycle Grampian, 2024). Cycle Grampian provides guidance for cyclists, emphasising the need for caution at level crossings and encouraging the use of safer public crossings.

Australia has implemented active pedestrian level crossings in Adelaide, incorporating automated gates, improved signage, and audible warning devices (Government of South Australia, 2021).

Another Australian study examined factors influencing risk at level crossings, analysing unsafe road user behaviour, risk perceptions, and attitudes (Read et al., 2021). The study revealed a lack of attention to the interplay between level-crossing design and user decisions.

A Croatian study simulated a pedestrian and cycle underpass using PTV Vissim software, exploring its effectiveness as a solution to replace a problematic level crossing (Grabušic and Baric, 2023).

Another Australian study investigated road user perceptions of train horn benefits, highlighting potential resistance to reducing horn usage (Larue et al., 2024).

A US study assessed the effectiveness of pedestrian signalling strategies at level crossings, demonstrating that action-inducing and emotionally motivated signals are more effective than purely informational signals (Ahmed et al., 2024).

An Indian study analysed pedestrian and cyclist violations at level crossings, finding that train characteristics, level crossing operation, and personal characteristics significantly influence violation behaviour (Vivek and Mohapatra, 2023).

The research reviewed highlights the crucial role of understanding pedestrian and cyclist behavior in enhancing level crossing safety. Effective interventions involve a combination of physical improvements, educational initiatives, and public awareness campaigns. Further research is needed to understand the complex interactions between level-crossing design, user behaviour, and risk perception.

The authors of this paper used a road safety audit (RSA) to inspect the railway crossings, which is a detailed technical safety inspection of road infrastructure projects during the operation (Ladich & Miletics, 2023). The purpose of the road safety audit is to ensure safe operation of the road, increase the safety of road users, and solve potential traffic safety issues.

The authors also used the Driver Behavior Questionnaire (DBQ) for a more detailed assessment of the irregularities of road users; this is an existing method that has already been used, for example, in Denmark (Martinussen et al., 2013). Sweden, the USA, Canada and in the UK also applied the DBQ, revealing in detail the behaviour of motorists on public roads (Af Wåhlberg et al., 2011). The authors of this paper used the DBQ to find out how pedestrians and cyclists rate the different ways in which level crossings are provided and how dangerous they are perceived to be. However, evaluating level crossings alone is not enough, which is why these road users were also asked to rate road junctions in terms of danger. The results are shown in the graphs below.

## 3. Road Safety Inspections of the facilities of sustainable transportation modes

The authors of this paper examined 10 level crossings in 2023 to investigate how the Road Safety Inspection (RSI) can be applied to road-rail level crossings. The study also recorded the behaviour of pedestrians and cyclists at level crossings. At one of the locations, although the level crossing is equipped with a labyrinth guardrail (e. g., at the railway crossing near Pétfürdő railway station), the pedestrian can simply bypass it, endangering his own safety. The labyrinth guardrail is intended to ensure the safe crossing of pedestrians, who must turn twice before crossing the tracks, thus forcing them to be cautious and to check whether a train is approaching the crossing. The pedestrian in the picture probably saw the use of the labyrinth guardrail as a waste of time and decided to bypass it. In Győr, at the Jereváni street crossing, cyclists were also part of the investigation. This is illustrated in Figure 1.

*Figure 1: Irregular crossing of a cyclist at the crossing (left); A cyclist crosses the crossing in the opposite direction to the cycle path (right) (Ladich and Miletics, 2023)*

Both cyclists are observed to be crossing irregularly; their decision to shorten the distance may have been influenced by the fact that a busy road crosses the level crossing; on one side of the crossing, there is a junction with traffic lights, a roundabout, a little further on, and between the two a road junction with traffic signs, where pedestrian crossings and joint pedestrian and cycle crossings are indicated by flashing yellow signs next to the signs. In heavy traffic, pedestrians and cyclists must wait a long time to cross. For this reason, they choose to cross the level crossing opposite the traffic lane, thus avoiding the need to cross first. In addition, in the diagram on the right, the cycle lane in the direction of travel is only closed on one side by the level crossing, not on the other, so the cyclist in the diagram cannot see the current signal from the light barrier. The pedestrian and bicycle crossing shown on the left is closed on both sides by a barrier, but if pedestrians are allowed to cross in both directions, cyclists can only cross in the direction of travel. Crossing against the direction of travel is irregular.

The 10 level crossings examined above were selected from level crossings in Hungary. Important criteria for the selection of the crossings were the type of security devices, whether there are pedestrian or cycling facilities (pavements, cycle paths, share pavements and cycle paths), the speed allowed on the crossing railway line and whether the crossing is located inside or outside a built-up area.

Among the railway crossings in Table 1, Komárom, Almásfüzitő and Győr have cycle paths, and in these crossings the cycle path is protected by light barriers and half-barriers. In addition to the railway crossing in Zirc, there is also a bicycle crossing with a "Start of level crossing" sign and a labyrinth barrier. The railway crossing in Pétfürdő has a sidewalk, and for the safe passage of pedestrians, a labyrinth barrier was established here as well. The Ács, Nagyszentjános, Vitnyéd, Nyúl and Vinye crossings do not have sidewalks or cycle paths; in the latter two, only the "Start of level crossing" sign calls attention to the moving trains.

*Table 1: Different types of level crossings in Hungary* ***[****Edited by Marcell Ladich****]***

| Serial No. | Railway Line number | Location | Railway crossing installation |
|---|---|---|---|
| 1. | 1. | Almásfüzitő | Light signal and half-barrier |
| 2. | 1. | Komárom | Light signal and half-barrier |
| 3. | 1. | Ács | Light signal and half-barrier |
| 4. | 1. | Nagyszentjános | Light signal and half-barrier |
| 5. | 8. | Vitnyéd | Light signal |
| 6. | 10. | Győr | Light signal and half-barrier |
| 7. | 11. | Nyúl | Traffic sign |
| 8. | 11. | Vinye | Traffic sign |
| 9. | 11. | Zirc | Light signal and half-barrier |
| 10. | 20. | Pétfürdő | Light signal |

# 4. Driver behaviour questionnaire – cyclist and pedestrians

The authors also used an anonymous questionnaire to investigate the behaviour of pedestrians and cyclists at level crossings. Within these two groups, a detailed analysis was made of those who use these modes of transport frequently, almost every day, to go to work/school, to run errands or to go shopping. An important question was how often they pass through level crossings when walking or cycling. In addition to ranking the different types of level crossings in terms of danger, respondents were asked to indicate how often they deliberately crossed them in an irregular way when using these two modes of transport. They also had to answer whether they looked around when they deliberately crossed when a level crossing was indicated as forbidden. Another important question for the study was whether the respondents had ever been involved

in a traffic conflict at a level crossing in the last 10 years. A traffic conflict situation is a traffic situation that almost ends in an accident, but thanks to chance or manoeuvres to avoid the accident (e.g. emergency braking, sudden change of direction), no accident occurs. Although the emergency braking mentioned in brackets refers to those using a vehicle, pedestrians can also find themselves in a similar situation, especially if they are not paying attention while crossing a level crossing (e.g. listening to music loudly with headphones or earphones, busy with their phone). The authors asked the above questions to motorised individual road users, i.e. those who use motorcycles and cars frequently, almost every day.

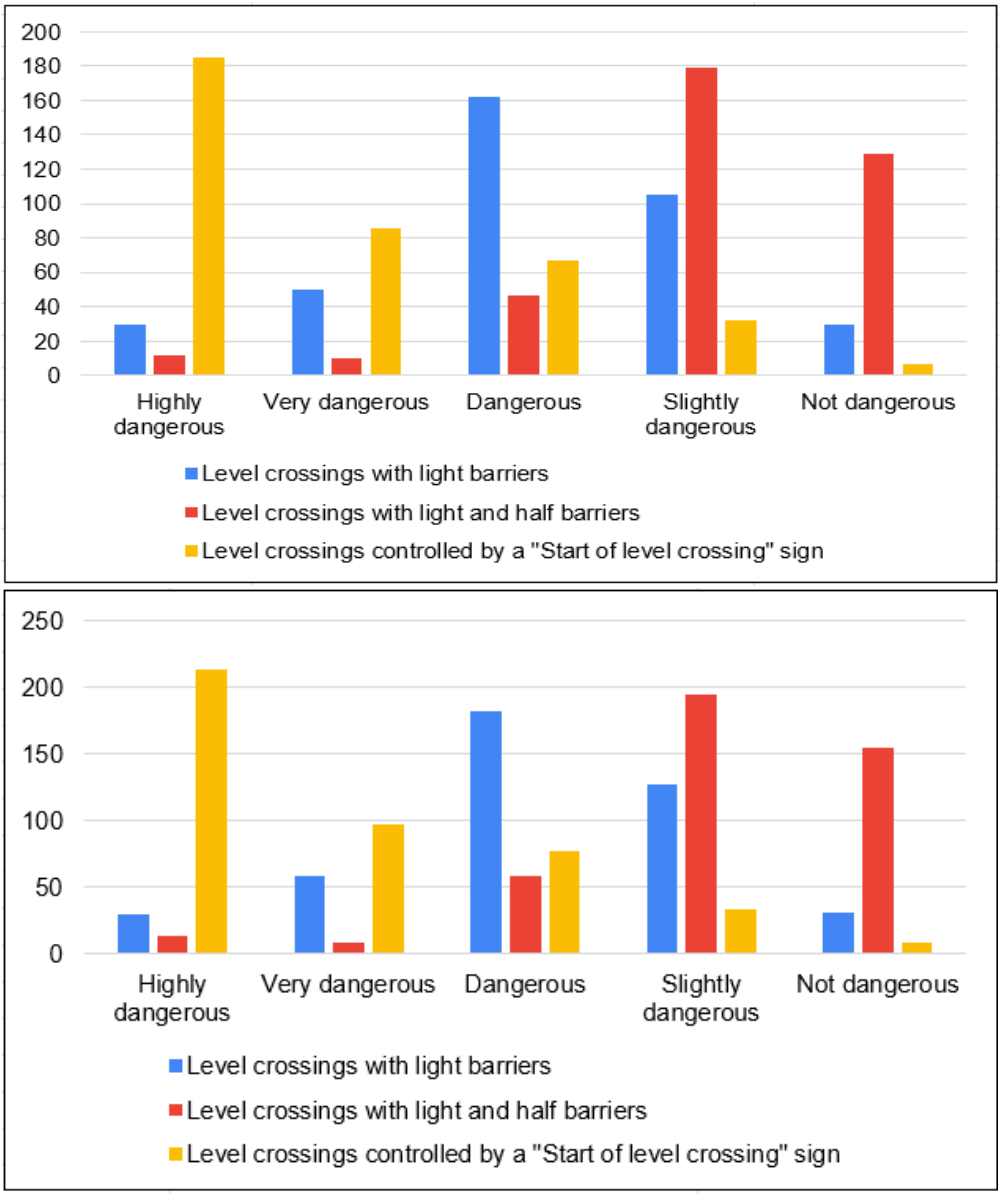
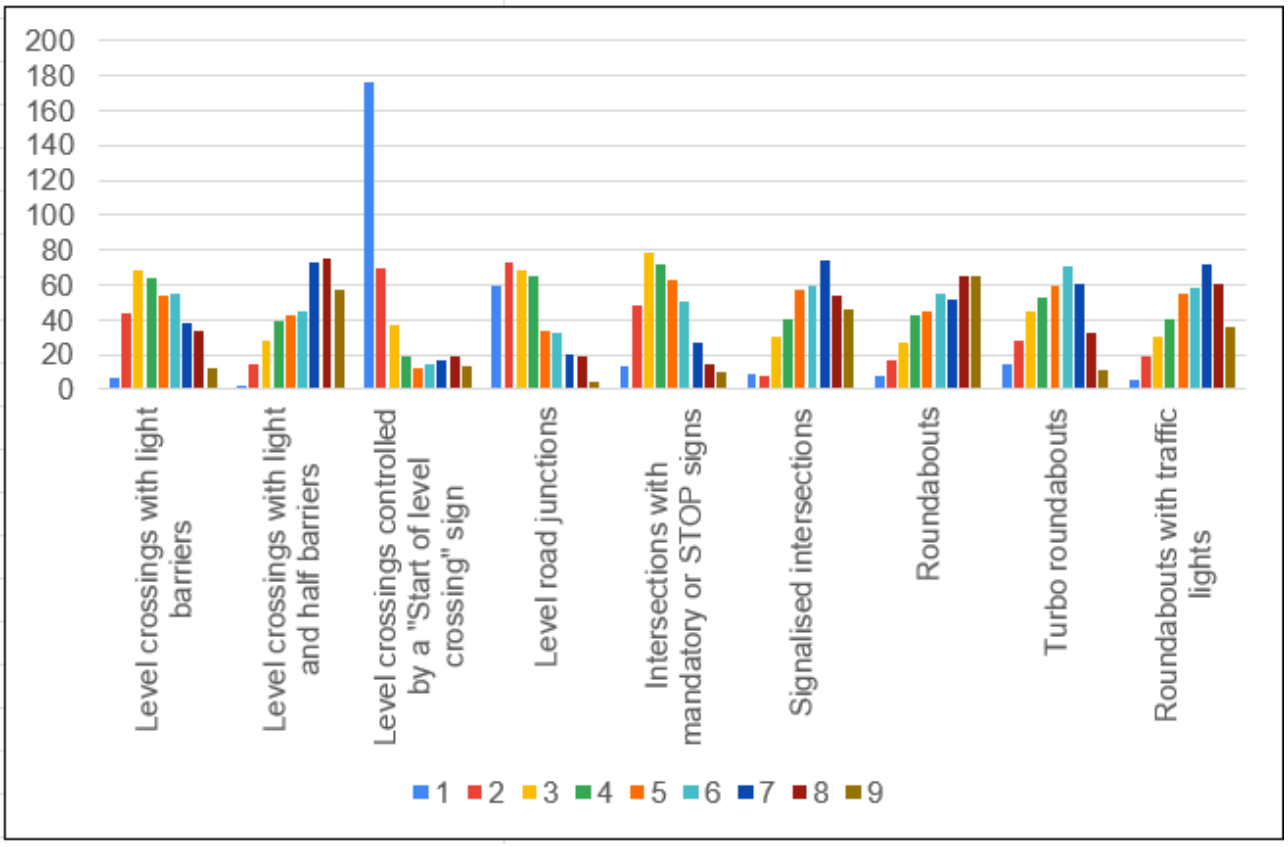



*Figure 2: Ranking of level crossings by pedestrian and cyclist danger (left); ranking of level crossings by driver and motorcyclist danger (right) [Edited by Marcell Ladich]*

Based on feedback from respondents, the authors have made a comparison of level crossings with different types of insurance using the diagrams in Figure 2. The authors investigated how the ratings of pedestrians and cyclists are like and differ from those of drivers and motorcyclists. Based on the responses to the questionnaire received so far, pedestrians, cyclists, drivers and motorcyclists have ranked the different types of level crossings according to the following diagrams.

It can be observed that railway crossings are the most dangerous crossings with a "Start of level crossing" sign. Level crossings with light barriers are considered dangerous, while those with light and semi barriers are considered the least dangerous. The likely reason for this is that the presence of a semi barrier as a physical barrier gives pedestrians a sense of security. A proportion of respondents do not consider this type of crossing to be dangerous. According to the questionnaire, most pedestrians and cyclists have never committed an irregularity at level crossings; and very few have rarely or very rarely crossed irregularly at level crossings. As for being careful at crossings, many pedestrians and cyclists never deliberately cross when the signal is red. However, some of them do look carefully when crossing under a forbidden signal. It is never safe to cross in a no-passing zone, especially at a level crossing with two or more tracks. Most pedestrian and cyclist respondents have never been in a conflict situation at a level crossing.

Like pedestrians and cyclists, car drivers and motorcyclists have different opinions about railway crossings with different secured methods. Railway crossings with the "Start of level crossing" sign are extremely dangerous, and railway crossings with light barriers and half barriers are considered the safest. Crossings with only light barriers are considered dangerous, but not particularly dangerous, because in those crossings, the approach of trains is already signalled by a light barrier, in contrast to crossings with a "Start of level crossing" sign, which they also approach with extra caution. The diagrams in Figure 3 illustrate the ranking of level crossings and road intersections by pedestrians and cyclists, drivers and motorcyclists.



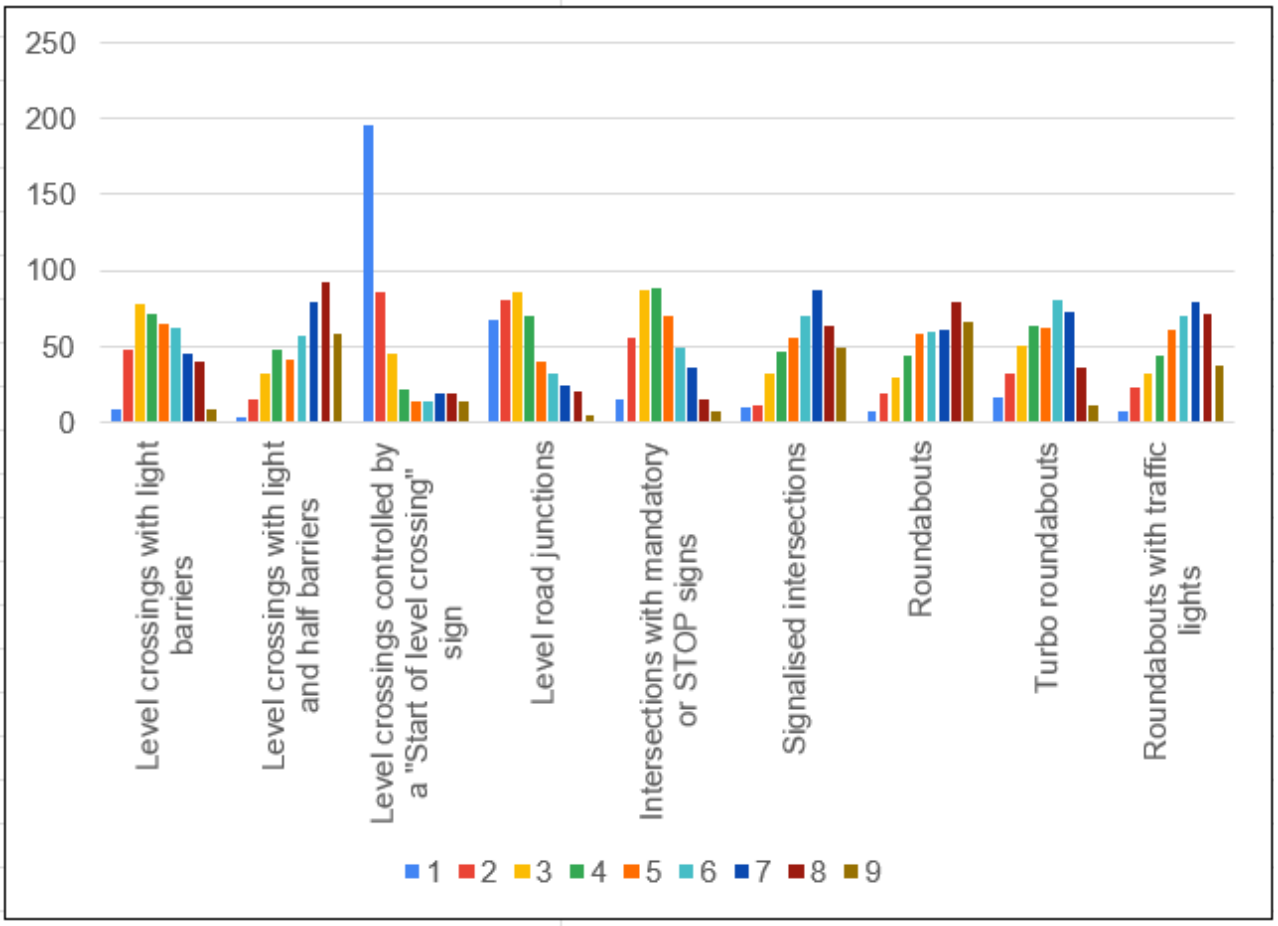



*Figure 3: Ranking of level crossings and road intersections in terms of danger to pedestrians and cyclists (left); ranking of level crossings and road intersections in terms of danger to drivers and motorcyclists (right) [Edited by Marcell Ladich]*

The respondents of the questionnaire had to classify railway crossings with different insurance methods and different types of road crossings on a scale from 1 to 9. 1 means the most dangerous, and 9 is the least dangerous. The diagram on the left (where pedestrians and cyclists have jointly classified intersections) shows that the railway crossing with the sign "Start of level crossing" is considered the most dangerous. Road-railway level crossings with light barriers are already considered less dangerous (and at the same time much safer), and railway crossings equipped with light barriers and half barriers are considered the safest. As far as road intersections are concerned, there is already a difference from railway crossings, as the pedestrian and cycling respondents, for example, consider level crossings to be the most dangerous, but not to the same extent as railway crossings with the "Start of level crossing" sign. It follows from this that pedestrians and cyclists approach railway crossings much more carefully than road intersections. Because accidents at railway crossings quickly make their way into the press, the sight of pictures taken at the locations can encourage them to always approach railway crossings more carefully. The diagram also shows that roundabouts are considered the safest of the road intersections: on a scale from 1 to 9, this junction received the most eights and nines. In addition, the respondents found intersections with traffic lights and roundabouts with traffic lights to be safer than level road intersections and signalised intersections.

The other part of the respondents to the questionnaire, i.e. car drivers and motorcyclists, evaluate railway crossings and road intersections similarly on a scale from 1 to 9. Among the railway crossings, the railway crossings with the "Start of level crossing" sign are considered the most dangerous, and the road-railway level crossings with light barriers and half barriers are considered the least dangerous. Regarding road intersections, the respondents have in common that they consider level crossings to be similarly dangerous, but intersections with signposts are considered less so. The presence of signs can already give a certain

sense of security, and the more equipped an intersection is, the more points it gets on the scale, i.e. the safer it is. Roundabouts were judged to be the safest intersections, just like pedestrians and cyclists. In both groups of respondents, it can be observed that railway crossings are always considered more dangerous than road intersections. The reason for this is that, as already mentioned above, the news of accidents at railway crossings can make road users cautious since the outcome of these accidents is much more serious than an accident on a public road or at a road crossing.

The risk assessment relates to the frequency with which pedestrians and cyclists, as well as drivers and motorcyclists, cross-level crossings irregularly. Most respondents never commit an irregularity; the questionnaire shows that pedestrians and cyclists cross irregularly very rarely compared to the other two groups; drivers and motorcyclists cross irregularly very rarely, but the former commit irregularities very rarely. Motorcyclists have the lowest rate of irregular crossings. Pedestrians and cyclists have a higher rate of very infrequent offences because, on the one hand, they can change their position more quickly and, on the other hand, they look around the level crossing and, if they see that the train is still a long way away, they cross the tracks quickly, risking their own safety, which is very dangerous. This is almost unheard of for drivers and motorcyclists.

It is worth comparing irregular crossings at level crossings with road intersections because the two diagrams above show that road intersections are perceived as less dangerous by pedestrians, cyclists, drivers and motorcyclists, even though accidents with more serious consequences can also occur at these locations. The feedback suggests that pedestrians and cyclists are more "courageous" in committing infringements at these locations, most of them not, but those who do so very rarely, infrequently and frequently cannot be neglected. The situation is somewhat better for drivers and motorcyclists, especially in the latter group, where the proportion of offenders is negligible. However, for the group of drivers (although most of them do not break the rules), the proportion of very infrequent and infrequent offenders is remarkable. However, frequent and very frequent offences are not common.

The reason why respondents consider level crossings to be more dangerous than road intersections is probably because of the different speed limits on the crossing traffic tracks (road, rail) as in Hungary; for example, trains can run at speeds of 80, 90, 100, 120 or even 160 km/h. The feedback received on irregularities shows that most road users are aware of the speed of trains and that the greater weight of trains means that accidents are more likely to occur.

# 5. Conclusions

Previous evaluations performed in this work show that the better equipped a level crossing is, the safer it appears to be, in the opinion of road users. However, it can be concluded that increasing the perception of safety, especially for pedestrians and cyclists, can give them the feeling that they can trust the equipment to work, so that they have the chance to avoid, for example, a labyrinth guardrail, because if the light barrier is working, this facility seems unnecessary. As a result, a routine may develop, which could lead to an accident. The above may also be true for cyclists, who, unlike car drivers, can look around more quickly and change position more quickly in the short term. Similarly, they can see the current light barrier from a distance and, if it is not flashing red, often cross without caution and without slowing down. They may also rely on the operation of the equipment and forget to be careful. But it is important to know that a light barrier is not the same as a traffic light: at level crossings in Hungary, a flashing white light only tells the user that the equipment is working, not that it is clear to cross. Overall, the mentioned groups ranked level crossings similarly in terms of danger, and all of them showed that a large proportion had never crossed irregularly, even during a "no trespassing" signal, or had never been in a conflict situation at a level crossing. Thus, most respondents are aware of the basics of behaviour at level crossings, but efforts should be made to improve the morale of sustainable transport users (e.g. pedestrians and cyclists) by raising their awareness of the dangers of level crossings and by educating them to use safety facilities (e.g. labyrinth guardrails) regularly to cross safely.

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# TOWARDS A SUSTAINABLE FRAMEWORK FOR INTEGRATING HBIM IN HERITAGE PRESERVATION

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**This study presents a sustainable framework for incorporating Heritage Building Information Modeling (HBIM) into heritage preservation based on insights from existing literature and practical applications. It highlights essential components such as stakeholder engagement, data management, modelling standards, and decision support systems. A case study of the timber roof in the Michelangelo Cloister, Rome, demonstrates the framework's practical use. The findings indicate that HBIM integration can significantly improve sustainability practices in heritage conservation, offering valuable insights for future maintenance and restoration efforts. This research provides new perspectives on the role of HBIM in heritage preservation, underscoring its significance for upcoming conservation initiatives.**

## 1. Introduction

Heritage buildings are more than just physical structures; they are living representations of our history, connecting us to our cultural identity and shared past. These structures serve as unique masterpieces within their communities, embodying architectural styles and techniques essential for understanding our built environment. Therefore, preserving these invaluable assets is crucial, as they reflect the stories and experiences that shape our communities.

Recently, Heritage Building Information Modeling (HBIM) has emerged as a transformative approach to heritage conservation. By extending the principles of Building Information Modeling (BIM), HBIM provides a comprehensive framework that integrates complex geometric and semantic data. This innovative methodology not only enhances geometric representation but also informs decision-making, improving the quality and effectiveness of heritage preservation projects.

In parallel, sustainability has gained significant emphasis globally, with heritage buildings playing a crucial role in establishing standards for sustainable practices within the construction sector. Utilising HBIM technology in heritage conservation can enhance sustainability efforts by providing comprehensive datasets and enabling efficient visualisation and analysis. Moreover, the integration of HBIM requires a framework that fosters collaboration among stakeholders and addresses the need for standardised data formats and interoperability. This framework should also consider the long-term sustainability of preserved heritage buildings, encompassing the maintenance and use of digital data to ensure environmental consciousness. To achieve this, it is essential to explore its evolution from BIM, the role it plays in heritage conservation, and how sustainability principles are integrated into it.

### 1.1. From BIM to HBIM

The preservation of cultural heritage has seen significant advancements in modern technologies, including 3D graphics, virtual reality, and BIM. These advancements have led to the emergence of HBIM, a specialised application of BIM principles for historical assets. HBIM integrates scanning, documentation, and model-

ling techniques, constituting a paradigm shift in the documentation, analysis, and preservation of historical structures (Murphy et al., 2009). Unlike traditional BIM, which focuses on new construction, HBIM creates 3D models based on pre-existing physical objects. It heavily relies on historical records, archival data, and geometric analysis of the existing structures, providing a digitally tangible and comprehensive form of building data storage for planning historical asset conservation (Bruno and Roncella, 2019). Therefore, it has evolved into a comprehensive framework, incorporating tools and techniques for managing, maintaining, understanding, enhancing, and documenting historical buildings (Allegra et al., 2020). However, the application of BIM in the heritage sector requires specialised tools and standards to address the complexity of historical structures. This includes a shift in perception to focus on the specific needs of historical buildings, such as irregular geometries, material degradation, and the integration of archival documents (Ewart and Zuecco, 2019). To support this, HBIM models rely on integrating archival resources, such as historical drawings, maps, and documentation, with modern surveying tools like laser scanning and photogrammetry. These methods ensure accurate geometric and semantic representation of the heritage structures. To address these challenges, developing HBIM, including parametric modelling, data management, and archive procedures, is crucial (Sampaio et al., 2021).

The importance of HBIM in cultural heritage conservation is growing, with researchers, planners, and policymakers recognising its value in managing, documenting, and conserving cultural heritage buildings (Dore and Murphy, 2017). It looks at how to use semantic information that is specific to heritage management and lifecycle data, as well as possible uses in planning reconstruction, preservation, and managing facilities (Heesom et al., 2020).

From the technical side, HBIM relies on specialised BIM software such as Autodesk Revit and Graphisoft ArchiCAD to develop detailed parametric 3D models of heritage structures. These platforms integrate both geometrical and semantic data, ensuring that models align with technical, archival, and restoration requirements. Open standards like Industry Foundation Classes (IFC) and CityGML are also used to guarantee interoperability and smooth data exchange between different systems. This approach fosters collaboration among architects, historians, and policymakers, enabling efficient and accurate heritage preservation.

## 1.2. HBIM in Heritage Preservation

HBIM plays a critical role in providing a holistic understanding of heritage buildings, enabling efficient management and conservation. Unlike traditional architectural documentation methods, HBIM offers a multidimensional approach that not only captures the physical and geometric properties of historical structures but also incorporates historical, cultural, and semantic data, which is essential for accurate conservation. In addition to architectural heritage, HBIM has been successfully applied to the preservation and improvement of historic transportation infrastructure, showcasing its adaptability across various heritage domains (Salah et al., 2024). This allows heritage professionals to visualise, document, and virtually reconstruct historical structures in a digital environment.

One of HBIM's notable advantages lies in its capability to generate libraries of parametric objects based on historical architectural data. These parametric libraries are vital for accurately representing the construction techniques and materials characteristic of various historical periods, enabling professionals to simulate restoration techniques and evaluate their potential impacts. Typically, these libraries are built through a combination of digital surveys (e.g., laser scans) and archival research, thereby supporting the entire lifecycle of sustainable preservation (Osello et al., 2018).

The methodologies used in HBIM extend beyond simple 3D modelling; they encompass advanced data management, including the archiving of historical materials and the integration of semantic information related to heritage management. The above-mentioned BIM software, combined with plugins like Dynamo or Grasshopper, allows for more complex parametric modelling and data integration, facilitating the creation of detailed digital twins of heritage assets. (Sampaio et al. 2021) have further investigated these HBIM methodologies and technologies in the context of heritage efforts. However, despite its potential, the incorporation of HBIM into heritage preservation poses challenges, such as concerns regarding the compatibility of fire safety software (Frosini et al. 2016).

## 1.3. Sustainable Heritage Preservation

### 1.3.1 Integrating HBIM Frameworks for Enhanced Sustainability

The preservation of historic buildings requires a balanced approach that considers environmental, economic, and social factors, making sustainability a key component of any preservation strategy (Karimi et al., 2022). Historic structures present unique challenges, such as the need to use compatible materials and preserve authenticity, which complicate sustainable preservation efforts (Loli and Bertolin 2018). To address these challenges, a systematic framework for sustainable heritage preservation is necessary. This framework should incorporate advanced tools such as monitoring, diagnosis, sensing technologies, material design, and Information and Communication Technology (ICT) tools, as highlighted by (Masini and Soldovieri, 2017). Additionally, indicators capable of measuring the sustainability of urban heritage sites are required, focusing on governance, technology, and social, economic, and environmental dimensions (Cho et al., 2022).

Integrating BIM into sustainable design has proven to be complex, particularly in large-scale infrastructure projects such as green highway construction. Despite its potential, BIM integration faces significant barriers, underscoring the need for comprehensive frameworks to overcome these challenges (Mohamad et al., 2023). Recent studies, such as (Rooshdi et al., 2021), demonstrated how a well-structured framework can effectively merge BIM with sustainability objectives. Building on these insights, this paper applies a similar approach to heritage preservation, arguing that the integration of BIM frameworks in heritage settings through HBIM can significantly enhance sustainability efforts in the conservation of historic buildings.

In this context, the proposed HBIM framework should facilitate the development of sustainable business strategies, support the management of sustainability-related data (Ahmed and Sundaram 2007), and incorporate the relationships between operational parameters. It must also integrate sustainability assessments (Nawaz and Koç 2018), align with the United Nations Sustainable Development Goals, and promote principle-based sustainability reporting (Abeysekera 2022). Key components for the success of this framework include stakeholder collaboration, standardisation of data formats, interoperability, and long-term sustainability considerations. The role of HBIM in sustainability certification, particularly in Historic Building Certification with an emphasis on interoperability and data preservation, has been explored by (Žurić et al., 2023). These studies collectively underscore the potential of HBIM in enhancing the preservation process, particularly in the areas of preventive conservation, long-term redevelopment, and sustainability certification.

### 1.3.2 Integrating LOD, LOI, and LOA Specifications

Sustainable heritage assets preservation relies on Level of Detail (LOD), Level of Information (LOI), and Level of Accuracy (LOA) integration. These specifications ensure the comprehensiveness and expandability of databases, aligning with sustainable practices by providing a structured framework for preserving cultural heritage (Salvador-García et al., 2020). LOD describes the geometric accuracy and detail of model elements used in design and construction. It makes sure that HBIM models have the accuracy needed to show how unique and complicated historic monuments are, which is important for preserving heritage. To ensure the long-term sustainability of heritage preservation efforts, it is important to adhere to LOD standards and use interoperable frameworks in HBIM (García et al. 2018). LOI is model non-graphical information such as materials or historical context. Heritage preservation may benefit from a particular LOI to record the as-built condition and monitor the building post-intervention. LOA measures how accurately the model represents the existing structure. Heritage preservation requires the correct representation of historic buildings (Brumana et al., 2018). Better preservation, restoration, and management choices are made possible by this integration in HBIM, which gives a more comprehensive and accurate knowledge of historic buildings. By improving communication and collaboration among preservation stakeholders, recording the as-built state for future generations, enhancing resource efficiency, and supporting long-term planning and management, this integration helps maintain history sustainably. The reliability and ongoing relevance of our common cultural legacy are therefore protected by the HBIM LOD, LOI, and LOA standards, which enhance preservation efforts. However, HBIM has unique challenges that need customised LOD, LOI, and LOA specifications, which may need additional requirements, such as understanding the concept of Level of History (LoH), which further emphasises the importance of integrating additional historical information within HBIM models (Brusaporci et al., 2021), promoting sustainable behaviours, and adding more historical data to HBIM.

According to the discussions presented, this work proposes a sustainable preservation framework in HBIM, integrating them into the preservation process from surveying to management. The key elements of the proposed work are stakeholders, Data collection, standardisation, analysis, and decision-making. Therefore, this paper contributes to the advancement of preservation strategies by exploring framework development based on the examined case study of Historical Timber Structures.

The remainder of this paper is constructed as follows: Section 2 discusses the considered case study of this work. Section 3 shows the proposed framework for sustainable HBIM usage in preservation. The research findings and their related discussion are presented in Section 4, and finally, the conclusion and remarks of this work are summarised in Section 5.

# 2. Case study: Preservation of Historical Timber Structures

This section explores a case study of timber structure preservation considering the further enhancement of the previously developed framework by (Santini et al., 2023). Therefore, the practical application of a framework designed to integrate HBIM into historic preservation is discussed. The case study explored a methodology for sustainable intervention on historical timber roof structures. The study demonstrates the use of a multi-criteria decision-making (MCDM) framework to assess sustainability aspects in interventions for wood historical heritage, providing insights into maintenance and structural repair solutions. focusing on the roof of the Michelangelo Cloister in the Diocletian Baths in Rome, which is a significant example of historical timber roofs. The timber roof is part of the architectural heritage listed in the World Heritage List and is protected by UNESCO. Historical timber roofs like this one are often lacking in maintenance, leading to the loss of original examples over time. This case study serves as a practical example of applying a multi-criteria decision-making approach to ensure the preservation of cultural heritage while incorporating sustainable practices.

## 2.1. Overview of the Proposed Framework and its application

The proposed framework is a decision-making approach that aims to find the best and most sustainable intervention for the conservation and preservation of historical timber structures, represented by a sustainability index (SI). The framework combines tradition and innovation to achieve maximum quality with minimum intervention, emphasising sustainability in terms of environmental, economic, technological, historical, and social aspects, as shown in Figure 1. It involves analysing various intervention alternatives using HBIM and assessing them using the Analytical Hierarchy Process (AHP) and the Integrated Value Quantification Model for Sustainable Buildings ((Modelo Integrado de Cuantificación de Valor para Edificaciones Sostenibles (MIVES)) methodology.

The research team utilised HBIM to create accurate geometric models of the Michelangelo Cloister's timber roof, enabling them to gather quantitative data essential for applying the Multi-Attribute Value Theory (MAVT) method. Expert judgment was employed to assign weights to various criteria and indicators using the AHP, facilitating a systematic evaluation of the sustainability aspects of the intervention. The MIVES (Multi-Attribute Ideal-Point System) methodology was then used to identify the ideal conservation option for the timber roof. This involved defining the ideal points for each criterion and evaluating the performance of each option against these ideal points. The MIVES methodology allowed for the identification of the conservation option that best satisfied the stakeholders' and decision-makers' preferences while also visualising the trade-offs between different criteria. This approach enabled the creation of a quantified and comparable SI, which helped evaluate the sustainability of the proposed interventions.

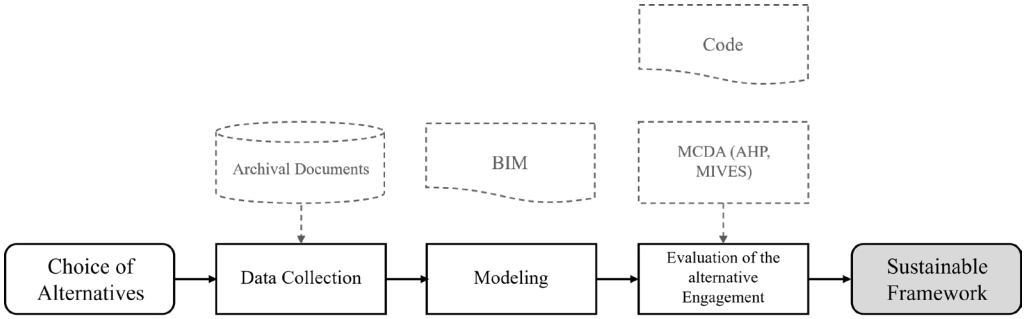


*Figure 1: Evaluation process for intervention options flowchart*

## 2.2. Analysis of the results

The results of the framework were presented as a quantitative SI that considered different intervention alternatives, including diagnostic tasks. The analysis compared the various intervention alternatives from environmental, economic, structural, and social perspectives. By examining multiple scenarios and weighing various criteria and indicators, the framework aided in decision-making processes regarding conservation and structural safety in heritage buildings. Where the MAVT and MIVES methodologies were applied in conjunction with the HBIM-based decision-making approach to evaluate the different conservation options for the timber roof of the Michelangelo Cloister in Rome. The results of the MAVT and MIVES analyses were used to identify the most suitable conservation option, which was then validated through a decision support system (DSS). Overall, the case study demonstrated the applicability of the proposed framework for assessing the sustainability of interventions on historical timber structures. Furthermore, the framework's ability to provide insights for decision-making showcased its efficacy in real-world scenarios.

# 3. An Enhanced Framework Proposal for Sustainable Integration of HBIM in Heritage Preservation

Preserving heritage buildings requires a sustainable and comprehensive framework that sustainably integrates HBIM. This framework, as proposed by multiple researchers (Salvador-García et al. 2020; Woodward and Heesom 2020), emphasises the need for a smart, open platform to manage the complexity of built heritage resources. It must integrate cultural significance into digital models while addressing challenges related to information management and project coordination.

Based on the case study described in Section 2, this paper proposes a sustainable framework for heritage preservation that incorporates several enhanced components, as shown in Figure 2.

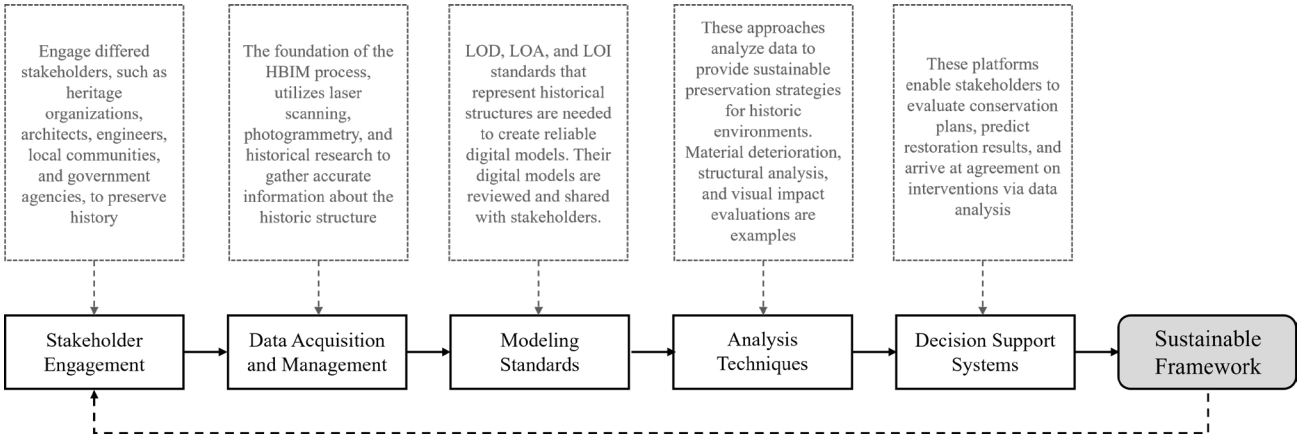


*Figure 2: The key elements of a Sustainable Framework*

At its core, stakeholder collaboration is essential, requiring the involvement of a diverse group of experts, including architects, historians, conservationists, policymakers, and local communities. Inclusive dialogue and transparent decision-making enable stakeholders to devise preservation strategies that balance conservation goals with modern needs and sustainable practices.

The framework emphasises data standardisation and interoperability, which are crucial for smooth communication among different HBIM platforms. By adopting common standards like IFC and CityGML, the framework ensures that various tools work seamlessly together, allowing for efficient modelling of historical buildings and supporting sustainable preservation efforts. IFC facilitates interoperability among software applications in the architecture, engineering, and construction (AEC) industry, providing a common language for sharing information and preventing misunderstandings. CityGML, on the other hand, focuses on 3D city models and urban information, making it valuable for urban planning and heritage management.

Integrating these standards enhances data usability and accessibility, enabling stakeholders to share and interpret information easily. This collaborative approach leads to better decision-making in heritage conservation, as all parties have access to reliable data, ensuring preservation initiatives are based on accurate information.

Sustainable practices are another key aspect of the framework, encompassing principles like adaptive reuse, energy efficiency, and resilience planning, which are integrated into HBIM workflows. By analysing building performance and simulating environmental impacts, stakeholders can make well-informed decisions that support the long-term sustainability of heritage assets.

The framework also emphasises lifecycle management and maintenance. Integrating HBIM with facilities management systems streamlines maintenance processes, optimises resource allocation, and enhances operational efficiency. This approach extends beyond initial documentation and modelling, incorporating ongoing data collection and monitoring to ensure the long-term preservation of heritage structures.

Community engagement and education are integral components of the framework. Involving the public in heritage preservation fosters a sense of ownership and stewardship, while educational programs and digital initiatives, such as virtual tours, enhance accessibility and promote awareness beyond the physical boundaries of the sites.

The proposed methodology for HBIM integration begins with surveying the existing heritage building and creating an initial model, which involves several stages: data acquisition, documentation, and geometric and non-geometric modelling. The model is then divided into the Project Information Model (PIM) and Asset Information Model (AIM) during the operating and maintenance phases. This approach ensures accurate documentation and preservation of heritage buildings while maintaining their historical and cultural significance through advanced data acquisition techniques and detailed models for restoration planning.

# 4. Discussion: Prospects and Advantages

The proposed framework for integrating HBIM into heritage preservation offers a comprehensive, sustainable approach, addressing key challenges in the field. By emphasising interdisciplinary collaboration and powerful data management, the framework ensures sustainability is woven into every aspect of heritage preservation. One of its standout features is its phased approach, which allows for adaptable execution and fosters improved cooperation among stakeholders. This flexibility is particularly useful when dealing with the unique characteristics and values of historic properties.

A major advantage of the framework is its strong focus on stakeholder engagement, ensuring that a wide range of perspectives are considered in the decision-making process. By involving diverse stakeholders, the framework promotes inclusive decision-making that aligns with the specific values of historic sites. Data standardisation and management further enhance this process by ensuring interoperability across platforms, which is crucial for preserving data integrity throughout the project's lifecycle. Incorporating sustainable practices into HBIM workflows also provides a significant benefit. These practices enable stakeholders to make informed decisions by simulating building performance and environmental impacts, supporting the long-term preserva-

tion of heritage buildings. Additionally, the framework's focus on lifecycle management and ongoing maintenance ensures that heritage assets are not only preserved but efficiently managed over time.

Despite its strengths, challenges remain, such as the need for technical resources, stakeholder coordination, and the adoption of standardised protocols, which may limit the framework's scalability. These challenges underscore the importance of continuous refinement and adaptation based on evolving technological capabilities and stakeholder needs.

Looking ahead, the construction industry faces growing resource scarcity, which requires a shift towards responsible resource management. The proposed "Hierarchy for Resource-Efficient Construction" model (Kuittinen 2023) suggests that responsible management of the existing building stock is a key direction for the industry. In this context, managing historic constructions is a particularly sensitive challenge that the optimised HBIM framework can effectively address.

The framework holds significant potential for future research and practice in heritage preservation, with opportunities for customisation based on diverse regulatory frameworks and cultural contexts. By integrating novel technologies and data administration techniques, it can further enhance preservation efforts, ensuring the sustainability of cultural heritage for future generations. Continuous evaluation and refinement will be essential in maximising its effectiveness and adapting to emerging challenges in the field.

# 5. Conclusion

The proposed framework for integrating HBIM into historic preservation constitutes a significant advancement in sustainable heritage management practices. Central to this framework is the principle of effective stakeholder engagement, which involves collaboration among a diverse array of participants, including conservation experts, local communities, and policymakers. This inclusive approach ensures that decision-making processes reflect the diverse values and objectives inherent in cultural heritage preservation.

The framework establishes a structured methodology that addresses the multifaceted challenges associated with historic preservation at each stage of the process, thereby promoting sustainability objectives consistently throughout. Its phased design enhances adaptability, enabling customisation to meet the specific needs of various heritage sites, which demonstrates its scalability across different contexts.

However, the framework faces challenges, including the availability of technical resources and the necessity for sustained stakeholder involvement. To optimise engagement, it is crucial to explore strategies such as workshops, public consultations, and collaborative planning sessions. These methods can significantly enhance participation, ensuring that all perspectives are integrated into the preservation process.

Given increasing environmental challenges, the integration of HBIM with sustainability principles is essential for preserving cultural heritage for present and future generations. Future research should prioritise expanding the framework's applicability to a broader range of heritage sites while refining engagement strategies. Such efforts will enhance the framework's overall impact and ensure its sustained relevance and effectiveness within the dynamic field of heritage preservation.

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# EVALUATING THE FERMENTATION POTENTIAL OF AGRICULTURAL MATERIALS AND FOOD-PROCESSING BYPRODUCTS

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This study investigates the fermentability of various agricultural raw materials using Liquid State Fermentation (LSF), a new approach in animal feed that could transform pig and poultry nutrition worldwide. Probiotic bacteria are key in this process, enhancing feed quality and digestibility by producing organic acids and enzymes that improve digestion and support animal health. This advancement reduces reliance on antibiotics, supporting sustainable farming practices. Building on previous research, this study developed a basic fermentation recipe using Distiller's Dried Grains (DDGS) or Corn Gluten Feed (CGF) as substrates. Two fermentation starters were tested: RS-L Health (Dr. Ferm) starter culture and microbes from fresh sweet whey. The study aimed to evaluate microbiological outcomes to compare the fermentability of different raw materials and feed mixtures. Throughout the fermentation process, continuous pH monitoring and microbiological culturing enabled quantification of viable cell counts for various bacterial species in the ferment. Statistical analyses were conducted to determine the effectiveness of different inoculants. Results indicated that the final pH of all products was consistently lower than the initial pH, with the most pronounced decrease observed in the DDGS mixture inoculated with whey. These findings underscore the potential of LSF to produce high-quality, sustainable animal feed.

## 1. Introduction

One of the key challenges today is the management and utilization of byproducts from food production processes, such as Distiller's Dried Grains (DDGS), Corn Gluten Feed (CGF), and whey. These byproducts are inevitable outcomes in the production of starch, cheese, and ethanol, making their alternative use a crucial area of research. Previous studies have explored the industrial applications of various agricultural byproducts. For instance, DDGS offers versatile usage options, including human food, biomass, pet food, and fermented feed (Buenavista et al., 2021). Likewise, CGF is highly nutrient-dense and can easily serve as a feed ingredient due to its high crude protein content (Wu et al., 2020). International practices reveal that only approximately 50% of the whey produced is utilized in alternative ways, despite its potential in industrial fermentation, animal feeding, baby food, and more (Ásványi, 2005).

Finding efficient and cost-effective solutions for the storage, logistics, and use of these byproducts is critical. Recycling and reusing them in feed production presents a promising opportunity, particularly because of their high protein content, which can contribute to the creation of nutrient-rich, high-quality feed (Couto and Sanroman, 2006). Additionally, this approach can help reduce harmful environmental emissions. By repurposing these byproducts, the bioecological footprint remains lower, contributing to the sustainability

of agricultural practices (Sugiharto, 2022). Furthermore, these byproducts provide an excellent opportunity to test and develop innovative techniques, such as Liquid Phase Fermentation (LSF). LSF is widely used in pig and poultry feed production, yielding significant improvements in quality (Chiang et al., 2010; Alpár et al., 2023). This technology enables the fermentation of valuable feed materials, including those with higher fiber content, using probiotic bacteria. The fermentation process enhances the nutritional value, reduces antinutritional factors, and improves digestibility through microbial activity (Xu et al., 2012). Additionally, organic acids like lactic acid and acetic acid are produced during fermentation, which lower the pH and prevent the colonization of harmful pathogens in the animal's intestine (Jazi et al., 2017).

Therefore, quantifying these organic acids both qualitatively and quantitatively is essential, as they contribute to protecting the intestinal tract of animals. Future research will focus on these measurements. Our current research aims to monitor the fermentation process of feeds made from a combination of various agricultural raw materials and food industry byproducts using novel LSF technology. We will also investigate the microbiological and hygienic parameters of the ferments and feeds, as well as the final achievable pH value.

## 2. Material and methods

The entire process, including preparation, fermentation, sampling, and microbiological analysis, is outlined in Figure 1.

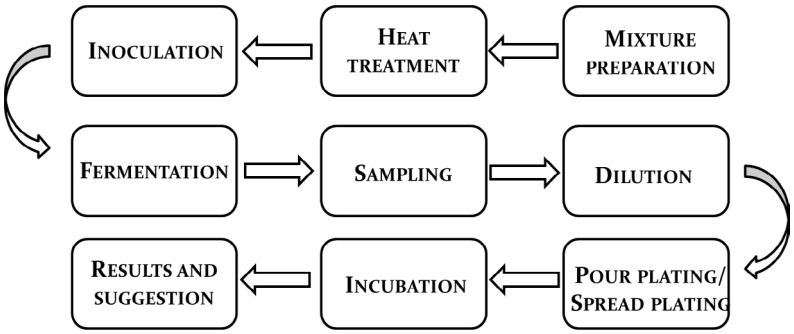


*Figure 1: Overview of the process and methodology*

The preparation of the test samples and inocula was conducted at the Department of Food Science, Albert Kázmér Faculty of Agricultural and Food Sciences, Széchenyi István University, in Mosonmagyaróvár. The mixture, comprising sunflower, wheat, rapeseed, and either CGF or DDGS, was pre-moistened and heat-treated at 55±3 °C for 20 min. The first inoculum tested was a Dr. Ferm lyophilized culture, containing a blend of ***Lactiplantibacillus plantarum*** and ***Enterococcus faecium*** strains. The inoculum was prepared based on a 24-h culture, using a DensiCheck device to adjust the cell concentration. The resulting 50 $cm^3$ suspension was added to the base mixture at the start of the fermentation process. The initial cell concentration was adjusted to approximately $10^5$ CFU/$cm^3$ by diluting 200–250 times. Controlled fermentation was carried out for 24 h, with continuous pH monitoring. The mixing speed was set to 700 rpm and the temperature to 37 °C. The second inoculum investigated was whey, a byproduct of semi-hard Óvári cheese production, obtained from the technological laboratory of the Department of Food Science at Széchenyi István University. In both cases, the base mixture was adjusted to 22 % dry matter and placed in the bioreactors of the fermentation system. Our trials involved four different combinations as shown in Table 1: the basic formulation (sunflower, wheat, rapeseed mixture) supplemented with either DDGS or CGF, and inoculated with two different inocula (Dr. Ferm bacterial culture and sweet whey). Each experiment was performed with three technical replicates and three parallel replicates.

*Table 1: Combinations of fermented feeds*

| Ingredient | DDGS + Dr. Ferm | DDGS + whey | CGF + Dr. Ferm | CGF + whey |
|---|---|---|---|---|
| | | Base (sunflower, wheat, rapeseed) | | |
| Base | + | + | + | + |
| | | Byproduct | | |
| DDGS | + | + | - | - |
| CGF | - | - | + | + |
| | | Inoculum | | |
| Dr. Ferm | + | - | + | - |
| Cheese whey | - | + | - | + |
| | | Water | | |
| Water | + | + | + | + |

DDGS: Distiller's Dried Grains with Solubles, CGF: Corn Gluten Feed.

## 2.1. Fermentation, sampling, and microbiological analysis

In our experiments, model fermentation was carried out using a Solaris Jupiter fermenter system with a working volume of 4.5 L (Solaris Biotech, Porto Mantovano, Italy). Throughout the fermentation process, stirring speeds were adjusted at 700 rpm, and the temperature was set to 37±1 °C. Key parameters, including pH, were monitored at 20-minute intervals using the Leonardo control program. Upon completion of the fermentation, samples from the four different preparations were subjected to standard microbiological and hygienic analyses (Table 2).

*Table 2: Standards for microbiological analyses*

| Microorganism | Standard method |
|---|---|
| Enterococcus faecium | BVL L 06.00-32 |
| Escherichia coli | ISO 16649-2:2001 |
| Enterobacteriaceae | MSZ ISO 21528-2:2017 |
| Coliforms | BS ISO 4832:2006 |
| Clostridium perfringens | MSZ EN ISO 7937:2005 |
| Lactobacillus / Mesophilic lactic acid bacteria | MSZ ISO 15214:2005 |
| Salmonella spp. presence/absence | MSZ EN ISO 6579-1:2017 |

To ensure accuracy, each sample was analyzed in triplicate. The procedure involved transferring 1 $cm^3$ of stock suspension into Petri dishes using a sterile pipette, followed by serial decimal dilutions, with fresh sterile pipettes used for each dilution. For the specific assessment of viable ***Enterococcus faecium*** cell counts, 0.1 mL of the diluted suspension was plated on CATC agar following standard protocols. The dilutions were evenly spread across the agar surface using a sterile spreading tool in a circular motion to ensure uniform distribution. To estimate average cell counts, formula (1) was applied:

$$\bar{C} = \frac{\Sigma c}{(n_1+0{,}1\times n_2)\times V\times d} \quad (1)$$

where:

Σc represents the total colonies counted across all selected plates,

V is the volume plated (in mL),

$n_1$ and $n_2$ denote the number of plates for the initial and subsequent evaluable dilutions, respectively,

d signifies the dilution factor.

Following cell count enumerations, statistical analyses were conducted. The arithmetic mean and standard deviation were calculated, and the data were analyzed using an F-test followed by a *t*-test. A P value of less than 0.05 was considered statistically significant.

# 3. Results and discussion

## 3.1. Changes in pH values during the fermentation process

The Leonardo software allowed for precise monitoring of pH values throughout the fermentation process, with data collection occurring every 20 min. After completing the fermentation, we reviewed the results, which showed a consistent decrease in pH across all experiments. This reduction in pH is attributed to the production of organic acids by lactic acid bacteria (Figure 2).

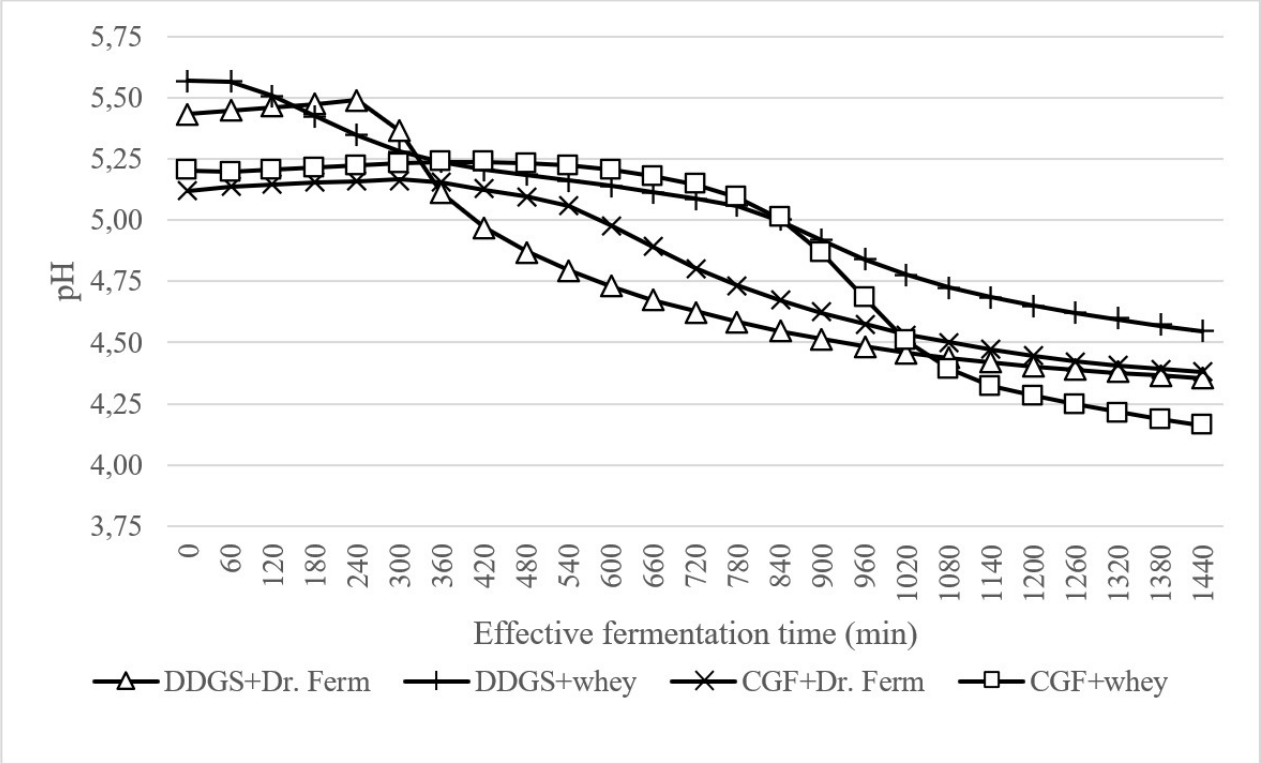


*Figure 2: Changes in pH values throughout the fermentation process*

Since the fermentation conditions, including incubation temperature and inoculum cell count, were consistent across all experiments, the pH values were primarily influenced by the varying buffer capacities of

the starting materials and their interaction with the microbial strains. No difference in pH was observed between DDGS + Dr. Ferm and CGF + Dr. Ferm ($P>0.05$). In contrast, differences ($P<0.05$) were found in the final pH values for all other comparisons. CGF + whey exhibited the lowest average pH value.

As Vuppala et al. (2015) explained, the reduction in pH is a result of microbial processes, where bacteria metabolize sugars and produce various organic acids. Similar findings were reported by Lee et al. (2023), whose experiments also demonstrated a drop in pH due to the high organic acid content produced by microbes during fermentation. In feeding trials, Missotten et al. (2015) successfully inhibited pathogens in the stomachs of pigs using low-pH fermented feed. Zhu et al. (2023) observed a comparable phenomenon in the cecum of broiler chickens.

## 3.2. Microbiological and hygienic properties of fermented feed

Microbiological evaluations identified several microbial groups that are regulated under Hungarian feed legislation (Ministry of Rural Development of the Republic of Hungary, 2012). These included ***Lactobacillus*** / mesophilic lactic acid bacteria, ***Escherichia coli***, ***Enterococcus faecium***, ***Enterobacteriaceae***, ***Clostridium perfringens***, ***Salmonella*** spp., and coliforms. The levels of ***Escherichia coli***, ***Clostridium perfringens***, and ***Enterobacteriaceae*** were found to be below the detection limit. These findings are consistent with those of Niba et al. (2009), who concluded that fermented feed can effectively reduce ***Escherichia coli*** counts. Coliform species were detected only in the combinations DDGS + whey and CGF + Dr. Ferm, at concentrations of $10^4$ CFU/cm$^3$ and $10^2$ CFU/cm$^3$, respectively. Alpár et al. (2023) also highlighted the beneficial effects of LSF feed against ***Salmonella*** and coliforms. The combination of DDGS + whey exhibited the highest probiotic effect, with a $\log_{10}$ count of 9.32 CFU/cm$^3$. These results are summarized in Table 3. According to Wendel (2022), probiotic effects are noticeable at cell concentrations above $10^7$ CFU/cm$^3$.

*Table 3: Post-fermentation viable cell counts**

| Bacterial species | Fermentation recipe | | | |
|---|---|---|---|---|
| | DDGS + Dr. Ferm | DDGS + whey | CGF + Dr. Ferm | CGF + whey |
| *Lactiplantibacillus plantarum* | 9.24 ± *0.04*$^a$ | 9.32 ± *0.02*$^a$ | 9.08 ± *0.07*$^b$ | 8.33 ± *0.54*$^c$ |
| *Enterococcus faecium* | 9.26 ± *0.02*$^a$ | 6.56 ± *1.39*$^b$ | 7.92 ± *1.14*$^b$ | 3.32 ± *0.62*$^c$ |

*$^{a–c}$ Means within a row without a common superscript differ ($P<0.05$). * Values are log10 CFU/ml means ± SD, based on nine observations (three samples × three replicates). DDGS: Distillers Dried Grains with Solubles, CGF: Corn Gluten Feed.*

# 4. Conclusions

The decrease in pH observed across all experiments is likely due to the production of organic acids by various lactic acid bacteria. However, our study did not include qualitative and quantitative analyses of these acids. Therefore, future research should focus on identifying and quantifying the specific organic acids produced. The most significant pH decrease occurred in the CGF + whey mixture, which also showed a high lactic acid bacteria count, making it a promising candidate for further animal trials. The reduction in pH contributes to an extended shelf life for the feed. The increased presence of lactic acid bacteria, including ***Enterococcus faecium***, along with their probiotic properties, can offer protective benefits to the gastrointestinal tract of livestock, enhancing both their health and production performance. In summary, this fermentation technique and its resulting products provide a strong foundation for the development of future fermented feeds that are free from antibiotics and fully align with sustainable agricultural practices. Additionally, the use of industrial byproducts in these fermented feeds offers an eco-friendly solution for farm animal nutrition.

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## Conflict of Interest:

The authors have no financial conflicts of interest to declare.

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# QUESTIONNAIRE-BASED PERSONALITY TEST OF TROTTER HORSES IN HUNGARY

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The selection of horses in equestrian sports during the last decades has mainly focused on physical attributes such as strength, speed, and size. However, concerning continuity and sustainability nowadays, other desirable traits like human-horse interactions could play a more important role because of the change of use and environment. So, we focussed on the behaviour of horses. 74 adult and trained trotter horses in Hungary were involved into a personality assessment. A questionnaire of 32 different behaviourally defined adjectives (BDAs) was completed. Horses were scored on each BDA by trainers using a seven-point scale (1 – not typically; 4 – ordinary; 7 – typically). Measures of sampling adequacy were the following: scary (0.77), fearful (0.74), insecure (0.71), reliable (0.65), intelligent (0.61), untrustworthy (0.53), aggressive (0.52), lively (0.44) and playful (0.41). These variables are strongly connected to all others. Anti-image correlations were very loose (-0.65-0.29). The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.635. The rotation of factors resulted in four different patterns of components (I: fearful, insecure, scary; II: aggressive, untrustworthy; III: intelligent; IV: lively, playful). The total variance of the four principal components was 77.79 %. Correlations between specific components and their associated behaviours were logical and consistent with the type of behaviours. Mapping the behavioural characteristics of horses can help the selection process through better adaptation to changed environments and requirements. For the separation of horses' behaviour and the expectations of trainers, an advanced questionnaire will be created using representative horses from the different groups.

## 1. Introduction

The European equine industry has a role to play in the achievement of the biodiversity strategy (Vial and Evans, 2015). According to O'Neill et al. (2018), it contributes significantly to social goods and is an interesting economic sector for EU regional sustainable growth. Liljenstolpe (2009) and Birke et al. (2010) reported that horses in Europe are not production animals anymore. Instead, they are sharers of different equestrian competitions, provide recreation possibilities via sport and hobby, take part in therapeutic processes, produce highly valuable milk, and meet and stock pharmaceutics, while for many people, it's like a pet or companion animal (Pongrácz and Kósik, 2023). Moreover, horses provide ecosystem services in many countries, especially for land uses and biodiversity preservation in different ways (Bigot et al., 2015; López et al., 2019; Ku et al., 2022).

Specific characteristics like conformation, gaits, and plenty of other performance traits have been selected for many purposes, resulting in the differentiation of domestic horses *(Equus caballus)* into morphologically distinct types or breeds worldwide, including in Hungary. Parallel with this, sports or competition performance results increased spectacularly, especially under professional conditions (Koenen et al., 2004). In between, the change in the use of horses affected the increased importance of temperament in terms of sustainability because today's leisure rider has completely different knowledge and practice compared to a professional horseman. However, temperament is one characteristic that is very difficult to assess objectively.

According to Goldsmith et al. (1987), personality can be defined as "a set of behavioural tendencies called traits that are present early in life". In other words, it reveals the uniqueness of the individual and is defined as "the characteristics of the individual that explain consistent patterns of emotion, thinking, and behaviour" (Pervin and John, 1997). Finkemeier et al. (2018) reported that terms like personality and temperament are used interchangeably within horse literature. The designation of temperament is "a set of behavioural dispositions that emerge early in life and are relatively constant in various situations and over time" (Lansade et al., 2008).

Animal personality literature was reviewed by Gosling and John (1999), Gosling (2001) and Gosling and Vazire (2002) and covered a broad range of species, including fish, reptiles, primates and other mammal species.

Equine personality assessment currently involves either the classification and assessment of observed behaviour (Le Scolan et al., 1997; Wolff et al., 1997; Visser et al., 2001; Seaman et al., 2002) or the completion of subjective questionnaires on the behaviour of individuals over a variety of situations (French, 1993; Morris et al., 2002; Momozawa et al., 2003, 2005). Questionnaire-based methods have been applied in various forms. Morris et al. (2002) employed an in-depth human personality rating system, whilst French (1993), and Momozawa et al. (2003, 2005) used behaviourally defined adjectives to create rating questionnaires. Due to the use of behaviourally defined adjectives the method reported by Stevenson-Hinde and Zunz (1978) originally created for rhesus macaques (Macaca mullata) has been adapted for the assessment of a variety of different species like cat (Felis catus), gorilla (Gorilla gorilla), spotted hyena (Crocuta crocuta), cheetah (Acinonyx jubatus), chimpanzee (Pan troglodytes), pig-tailed macaque (Macaca nemestrina), and so horse (Equus caballus). In addition, this assessment method can be applied in conjunction with principal component analysis (PCA) to identify underlying personality components and explore personality structure. Lloyd et al. (2007) and Danişan et al. (2024) used the same method for preparing a horse personality questionnaire (HPQ). In contrast, Le Scolan et al. (1997) scored situation-specific behaviours (e.g. fearful when ridden).

Danişan et al. (2024) summarized that the personality of horses may vary considering their age, sex and breed. Visser et al. (2001) observed that young horses (9 months) were more fearful and active than older ones (22 months). Similarly, Vidament et al. (2021) reported that 2-year-old horses were more fearful, reactive, and gregarious than 3-year-old horses. Sackman and Houpt (2019) determined that mares were less curious and more anxious than geldings. Breeds like Highland pony, Irish draft horse, French saddlebred, Thoroughbred, Angloarab, Arabian, Welsh cob and American quarter horse are often described as having breed-specific behaviours (Hausberger and Muller, 2002; Lloyd, 2008; Lloyd et al., 2008). Vidament et al. (2021) observed that personality differences between breeds concerned tactile sensitivity, with a lower sensitivity measured in ponies than in horses, particularly Anglo-Arabians. They also stated that fearfulness was the other trait that distinguished leisure ponies from the other breeds (sport horses being more fearful than ponies or draft horses). Among Norvegian horse breeds, Olsen and Klemetsdal (2017) researched the temperament of the Norvegian coldblooded trotter, and Berglund (2021) studied the genetic background of temperament traits of Standardbred trotters, but there is still a lack of scientific literature on personality traits of trotter horses.

Lansade and Simon (2010), Christensen et al. (2012), Fortin et al. (2018) and many others reported that the effects of personalities are appreciated in the learning processes of horses. Likewise, it is promising to select horses based on their personalities for appropriate disciplines (Rankins and Wickens, 2020). Through equine personality assessment and appropriate horse selection, Graf et al. (2013) and so Pierard et al. (2017) have shown that risks can be narrowed, horse-human interaction can be improved, daily sequences can be simplified, and horse management can be more reliable and comfortable. Concerning the successful future of the traditional turf in Hungary (Fehér and Török, 1983) it would be beneficial to have reliable temperament data of trotter horses as well.

This paper aims to evaluate the personality traits of trotter horses housed in the hippodrome in Hungary by using the Stevenson-Hinde and Zunz (1978) and Stevenson-Hinde et al. (1980) rating method and to create distinct personality classes of horses according to personality variables in horse personality questionnaire using latent class analysis. In addition, the adjective variables that formed the personality classes were evaluated, and the personality classes were compared.

## 2. Methods

A total of 74 adult purebred trotter horses from the Training Center of Alag (Hungary) were used within the scope of the research. The study group consisted of mares, stallions and geldings. All of the horses involved in the research are housed in the same hippodrome for at least 6 months. Horses with health problems were excluded from the study.

A questionnaire of 32 different behaviourally defined adjectives (BDAs) was completed, mainly adapted from Stevenson-Hinde et al. (1980), Morris et al. (2002), and Lloyd et al. (2008) due to the behaviour rating questionnaire's previous adaptability to other species were considered to be suitable for the assessment of horses. Some more adjectives were also added to further adapt the questionnaire for horses commonly used by horse owners and trainers. These also were considered to be suitable adjectives for the description of horse personality ***(Table 1).***

*Table 1: Behavioural definitions of some principal personality adjectives*

| Personality adjective | Behavioural definition |
|---|---|
| Aggressive [a] | Causes harm or potential harm to other individuals, both horse and human |
| Fearful [a] | Retreats readily from others or from outside disturbances |
| Insecure [a] | Hesitates to act alone; seeks reassurance from others |
| Intelligent [c] | Learns new things easily/fast benefits from mental stimulation |
| Lively [d] | Full of life |
| Playful [a] | Initiates play and joins in when play is solicited |
| Reliable [b] | Can be trusted to do things or behaves well might also be considered a safe horse to be with |
| Scary [d] | Suddenly get stressed |
| Untrustworthy [d] | Unable to be depended |

*[a] Adapted from Stevenson-Hinde et al. (1980).*
*[b] Adjectives derived from Morris et al. (2002).*
*[c] Adapted from Lloyd et al (2008)*
*[d] Derived from behavioural terms*

Horses were scored on each BDA by trainers using a seven point scale (1 – not typically; 4 – ordinary; 7 – typically). Instructions on how to fill out the questionnaire were given by a professional in the field of horse behaviour to the relevant trainers. Additionally, the experimenter rated all horses on completion of behavioural observations recorded by video camera.

Data were manipulated by Excel and statistical analysis was performed using the SPSS 24 (SPSS Inc., Chicago, IL) statistical software. To find groups or subtypes of personality variables of horses latent class analysis was used and classes were compared. Latent class analysis is a measurement model in which individuals can be classified into mutually exclusive and exhaustive types, or latent classes, based on their pattern of answers on a set of categorical indicator variables. Horse personality structure and its association with recorded behaviour were explored using principal component analysis (PCA). PCA is a statistical method for data compressing and revealing the structure of data. It groups the starting variables and compresses them into factor variables, which directly can't be recorded. There are no previously appointed dependent and independent variables in this method, but it aims to explore the interrelation of the variables. The PCA investigates the relationship of several variables, which are correlated to each other. Background variables were calculated from the correlation matrix of the parameters. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.635, suggesting that our data is suitable for factor analysis (KMO≥ 0.6). Measures of Sampling Adequacy (MSA) were the following by variables: aggressive (0.52), untrustworthy (0.53), intelligent

(0.61), lively (0.44), fearful (0.74), insecure (0.71), playful (0.41), scary (0.77) and reliable (0.65). These mean that all of these variables are strongly connected to all other. Anti-image correlations were very loose (-0.65 – 0.29). The rotation of factors (Eigenvalues >1) was done as outlined by the Varimax with Kaiser normalisation (Sváb, 1979).

# 3. Results and discussion

The mean and standard deviation values of the personality adjectives of trotter horses are summarised in Table 2. The most frequent personality adjectives were the intelligent (5.68), the reliable (5.30) and the lively (4.93). Data clearly present that the aggressive (2.51) and insecure (3.14) behaviour is not typical among trotter horses. This suggests that harmonious cooperation between humans and horses can develop relatively easily.

*Table 2: Mean and standard deviation values of the personality adjectives of trotter horses*

| Personality adjectives | Mean | Std. deviations |
|---|---|---|
| Aggressive | 2.15 | 1.718 |
| Fearful | 3.32 | 1.806 |
| Insecure | 3.14 | 1.658 |
| Intelligent | 5.68 | 1.472 |
| Lively | 4.92 | 1.742 |
| Playful | 4.50 | 1.777 |
| Reliable | 5.30 | 1.757 |
| Scary | 3.57 | 1.791 |
| Untrustworthy | 3.18 | 2.050 |

Standard deviations of all personality adjectives are high because these traits are determined by plenty of different factors, e.g. age, housing system and feeding, training method, etc. Rankins and Wickens (2020) revealed that personality could be modified through environment and experiences. Considering that management and environmental factors related to horses may affect personality components, it should also be taken into consideration that not being able to observe some of the behaviour of horses may be limiting in terms of determining some personality traits. Moreover, the horses in the research do not have paddocks. This situation causes them to be unable to show some of their intra-species social behaviours. The same fact was detected by Danışan et al. (2024). For this reason, the sociable, playful, and popular personality traits of horses, which are the components of the "sociability" personality classes, were determined by Lloyd et al. (2008) and could not be determined by the observers who conducted the questionnaire in this study. Last but not least, the individual differences within the breed could also be important.

In five cases, the Pearson correlations *(Table 3)* were positive and medium strong ($r \geq 0.57$, $P \leq 0.01$, $P \leq 0.0001$), e.g. aggressive vs untrustworthy; fearful vs insecure, fearful vs scary, insecure vs scary. A very loose negative correlation ($r = -0.329$) was observed between the scary and the reliable that seems to be clear.

*Table3: Pearson correlations of the personality adjectives of trotter horses*

| Traits | Agressive | Untrustworthy | Intelligent | Lively | Fearful | Insecure | Playful | Scary |
|---|---|---|---|---|---|---|---|---|
| Untrustworthy | **0.642**** | - | | | | | | |
| Intelligent | -0.127 | -0.153 | - | | | | | |
| Lively | 0.086 | -0.050 | 0.235 | - | | | | |
| Fearful | 0.214 | 0.169 | -0.243 | -0.057 | - | | | |
| Insecure | 0.137 | 0.190 | -0.296 | -0.138 | **0.658**** | - | | |
| Playful | 0.043 | -0.085 | 0.021 | 0.389 | -0.158 | -0.033 | - | |
| Scary | 0.239 | 0.271 | -0.298 | -0.003 | **0.649**** | **0.574**** | -0.168 | - |
| Reliable | -0.255 | -0.121 | 0.583 | 0.093 | -0.372 | -0.461 | 0.004 | **-0.329*** |

**= P≤0.01; **= P≤0.0001*

Analysing the value of commonalities is important in applying PCA *(Table 4)*. This number shows to which extent (percentage) all principal components used in the study define a given parameter. Data were well-defined (from aggressive: 0.832 to insecure: 0.728) in all cases were higher than 0.7. This value means that this database is convenient for the PCA.

*Table 4: Communalities of the personality adjectives of trotter horses*

| Personality adjectives | Mean |
|---|---|
| Aggressive | **0.832** |
| Fearful | 0.803 |
| Insecure | **0.728** |
| Intelligent | 0.796 |
| Lively | 0.754 |
| Playful | 0.759 |
| Reliable | 0.756 |
| Scary | 0.741 |
| Untrustworthy | 0.832 |

*Table 5: Eigenvalues, explained variance, principal components structure (rotated loadings) of the personality adjectives of trotter horses*

| Personality adjectives | Components (loading) | | | |
|---|---|---|---|---|
| Aggressive | 0.114 | **0.889** | -0.118 | 0.119 |
| Fearful | **0.883** | 0.082 | -0.116 | -0.063 |
| Insecure | **0.799** | 0.027 | -0.297 | -0.024 |
| Intelligent | -0.133 | -0.075 | **0.871** | 0.118 |
| Lively | 0.062 | 0.054 | 0.286 | **0.816** |
| Playful | -0.172 | -0,042 | -0.170 | **0.836** |
| Reliable | -0.327 | -0.104 | 0.798 | -0.047 |
| Scary | **0.831** | 0.192 | -0.106 | -0.054 |
| Untrustworthy | 0.118 | **0.897** | -0.042 | -0.107 |
| Eigenvalues | 2.292 | 1.661 | 1.635 | 1.413 |
| % of variance | 25.467 | 18.456 | 18.165 | 15.704 |

Four principal components (PC) were defined in our study *(Table 5.)*. Determination factor loadings in the *first PC* were from 0.799 to 0.883. Fearful, insecure and scary personality adjectives have highly definitive effect (factor loads ≥0.799). The factor loads were very low in those cases of aggressive (0.114), untrustworthy (0.118) and intelligent (-0.133). The Eigenvalue of the first PC is very high (2.292) with a 25.47 % eigenvalue variance. In the *second PC*, aggressive (0.889) and untrustworthy (0.897) traits were more dominant than the others. The Eigenvalue of the second PC is relatively high (1.661) with an 18.46 % eigenvalue variance. The Eigenvalue of the third PC was similar (1.635) with an 18.165 % variance. In this case, the effect of intelligence (0.879) was the most important trait. Lively (0.816) and playful (0.836) were the more favourable (≥0.816) traits on *the fourth PC* with 15.7 % eigenvalue variance. After 5 iterations, a very high total variance (77.79 %) was calculated.

# 4. Conclusions

Horse breeds have differences concerning temperament, but there is just a limited number of relevant existing literature on trotter horses, and so in Hungary. In our study, the temperament of trotter horses was evaluated by behaviourally defined adjectives for providing knowledge and tools to a sustainable horse industry under present conditions. Results suggest that harmonious cooperation between humans and horses can develop relatively easily because the most frequent personality adjectives were intelligent, reliable and lively. Data clearly show that aggressive and insecure behaviour is not typical among trotter horses. It is thought that fearful, insecure and scary trotter horses should be paid attention to during training, while lively and playful traits are relatively less important. We also concluded that in order to fully understand the personality of horses, it is crucial to observe their intra-species interactions.

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# DIGITAL SOLUTIONS IN BANKING AS A CATALYST FOR SUSTAINABLE DEVELOPMENT

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As technology increasingly affects every aspect of our lives, it seems to be a rightful expectation that the process of digitalisation should take place in a sustainable manner. Sustainable digital transformation requires not only the development and the use of digital tools but also takes advantage of their potential for the implementation of ESG issues.

Digital transformation in the banking sector has brought about substantial changes in the financial industry worldwide. This paradigm shift has been driven by two primary factors. On the one hand, there is an escalating customer demand for advanced technologies that offer convenience, speed, and security. On the other hand, the widespread accessibility of the Internet has made digital banking solutions feasible and desirable.

The research is based on the qualitative content analysis (QCA) of sustainability reports of OTP Bank, UniCredit Bank and CIB Bank in Hungary. By determining the relevant concepts and conceptual relations on the basis of the clusters and their assigned material topics applied in the reports, the paper aims to explore their link to digital transformation and their compliance with the corresponding SDGs. The findings indicate that, based on the sustainability reports analysed, the digitalisation efforts of banks show limited commitment to sustainability.

## 1. Introduction

Research on sustainable development has gained considerable attention over the past decade. Parallel to the focus on sustainable development, digital transformation has come to the forefront as a challenge not only for businesses but also for the society, as well. Even the UN 2030 Agenda for Sustainable Development (2015) acknowledges the high potential of ICT to speed up development by bridging the digital divide and developing knowledge societies. The COVID-19 pandemic has accelerated digital transformation. In particular, the need for digital connectivity has replaced physical interactions between consumers and providers, resulting in technology-based finances, low-cost computing, and data storage (BIS, 2021).

Digital transformation (DT) in the banking sector has led to the emergence of omnichannel banking, which enables customers to manage their finances through different channels, such as online, mobile or in-person, while still having a consistent user experience. Both banks and their customers benefit from digital transformation. While banks can take advantage of reducing their operating costs, saving time, optimising risk management practices, and widening their products and services, customers may enjoy fast and secure completion of transactions and have access to services even from remote areas.

The paper investigates how the digital transformation of the selected banks aligns with their sustainability efforts, based on their 2022 sustainability reports, using qualitative content analysis.

# 2. Literature review

There is only little research on the connection between digital transformation and sustainable development in the banking sector. The majority of research on digital transformation is based on macro-, industry-level analysis, higher education, and healthcare. Research on banks and digital transformation investigates the following topics: (1) the perceived impact of DT processes on banks' performance, with a focus on employees' attitude to digital transformation (Porfírio et al., 2024); (2) the impact of FinTech innovation on financial literacy (Ferilli et al., 2024;); (3) the efficiency of online customer service including the reduction of paper-based processes and the development of more efficient business strategies based on a large amount of data available (Becsei et al., 2023); (4) the impact of IT and non-IT employee relationships on digital transformation in the banking sector (Rodrigues et al.,2023).

Some studies explore the connection between digital transformation and sustainability. Burinskiené et al. (2022) analyse the correlation between digitalisation and Sustainable Development Goals (SDGs) in EU countries using Eurostat and UNECE data. ElMassah and Mohieldin (2020) focus on how e-Government and Big Data in developing countries can support SDGs by helping policy-makers track progress and improve programmes based on real-time data.

The current literature also presents how sustainable companies' digitalisation processes are based on their sustainability reports. Niehoff (2022) claims that the worldview on sustainability of a company can be determined through the rhetoric of the sustainability report. Banks' non-financial reporting is also the focus of attention by Aguado-Correa et al. (2023), making a proposal for better comparability, as well as Vargáné Kiss, 2023 assessing banks' economic performance based on their sustainability reports.

In conclusion, the majority of the studies cited are centred around banks and digital transformation, revealing how digitalisation affects employees, customers, society and company strategy. In addition, digital transformation is also explored in a broad sense, encompassing EU countries and in a narrow sense, targeting a particular field such as e-government. Another research perspective targets the quality of sustainability reporting practices of companies and banks from a general point of view. However, none of the papers mentioned of above investigates digital transformation in banking as reflected in their sustainability disclosures. All this indicates a research gap and justifies a righteous need for the topic of the current paper by answering the research questions raised in the Introduction through a thorough analysis.

The paper addresses a research gap by investigating how a connection between digital transformation and sustainable development is reflected by sustainable development goals. Making a qualitative content analysis of the sustainability disclosure of three major commercial banks in Hungary from the 2022 business year, the paper attempts to find an answer to the following research questions:

Q1: In what way does digital transformation contribute to the sustainability endeavours of commercial banks?

Q2: Which SDGs are aligned with digital transformation (DT)?

# 3. Methodology

The paper is based on qualitative content analysis (QCA) involving the 2022 sustainability reports of CIB Bank, Unicredit Group and OTP Banking Group. It extracted information from texts by manual method revealing the existence of concepts (principles or ideas) and their conceptual relations (associations with principles or ideas) as reflected by clusters (a group of similar things, here also strategies) and their assigned material topics (topics that represent an organization's most significant impacts on the economy, environment, and people). Following this process, a link to digital transformation was identified, and finally it was explored in what way the selected concepts together with their conceptual relations as reflected by the clusters and their material topics, as well as their link to digital transformation were in compliance with the respective sustainable development goals (SDGs) based on the principles of the UN 2023 Agenda (2030). These SDGs are defined and described in the Discussion and results section.

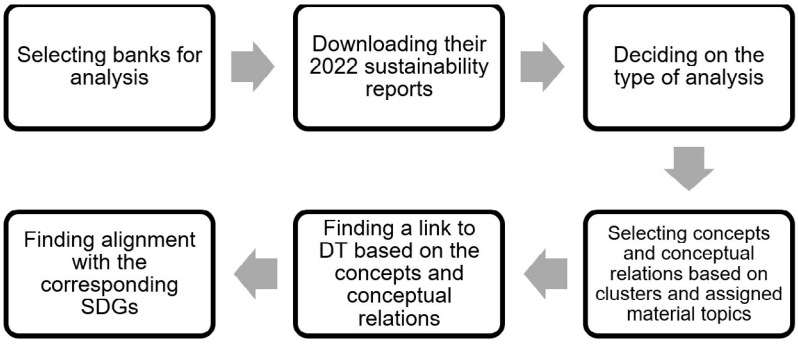


*Figure 1: Steps of the qualitative content analysis*

# 4. Discussion and results

This part gives of brief overview of the banks analysed and answers the research questions.

## 4.1. CIB Bank

In 2022, CIB Bank, a subsidiary of the Intesa Sanpaolo Group, defined the key strategic directions and objectives for the period 2022 – 2025, among which the further advancement of digital transformation plays a key role. CIB Group's non-financial statement is built on four main themes: governance and risk management, society, people, environment and climate change, each of which several material topics are assigned to. The bank's non-financial statement is a separate chapter of the Group's Business and Management Report, following the consolidated financial statements.

*Table 1: CIB Bank – Link between digitalisation and sustainability*

| CONCEPTS | CONCEPTUAL RELATIONS | | LINK TO DT | SDGs |
|---|---|---|---|---|
| | CLUSTERS | MATERIAL TOPICS | | |
| DIGITAL TRANSFORMATION | Governance and risk management | Innovation and digital transformation | Service quality, online payments and billing, digital customer experience, home banking | 9, 12 |
| | Society | product innovation and service models | Product innovation, digitalisation of services, IT security training for employees | 9 |
| CYBER SECURITY | Governance and risk management | cybersecurity | IT risk | 9, 12 |
| FINANCIAL INCLUSION | Society | Access to credit and financial inclusion | Financial inclusion, spread of financial culture | 4,5,8, 9,10 |
| | | Community support | Financial inclusion, education and spread of financial culture | 4,11 |
| EMPLOYEE DEVELOPMENT | People | Retention, enhancement | Investment in trainings, online education | 8, 10 |
| | | Well-being | Smart working | 3, 8 |
| | | employment protection | Knowledge retention, flexibility of employment | 8 |

*Source: Compiled by the author based on CIB Bank's Non-financial statement 2022*

As presented in Table 1, all the clusters, together with their material topics, are interwoven by digital transformation. The table shows only those clusters with their assigned material topics which are associated with the selected concepts (digital transformation, cybersecurity, financial inclusion and employee development) and correspondingly have a direct impact on SDGs. Therefore, the cluster Environment and climate change with their material topics (Transition to a sustainable, green and circular economy and Direct environmental impacts) are excluded. As digital transformation cannot be implemented without cybersecurity, the development of employees, the involvement of society (financial inclusion) and the strategies and operation of the bank (governance), all this should clearly be reflected by the corresponding SDGs. It is, however, not surprising that based on this, SDG 8 (Decent work and economic growth) and 9 (Industry, innovation and infrastructure) take the lead, followed by SDG 4 (Quality education), 10 (Reduced inequalities) and 12 (Responsible production and consumption), while SDG 3 (Good health and well-being, 5 (Gender equality) and 11 (Sustainable cities and communities) are mentioned only once. Some of these findings are also underpinned by the fact that in 2022, the digital customer ratio of the bank was 82.6 %, an increase of 5.15 % compared with the previous year and the percentage of CIB customers using a new product (e.g. online personal loan application) or service (e.g. QR code payments are via CIB Bank Mobile Application) through digital sales reached 46.2 % in 2022 (an increase of 53.8 % compared to 30.0 % in 2021) (CIB Non-financial statement, 2022, 28).

## 4.2. UniCredit Bank

UniCredit Bank is a subsidiary of the UniCredit Group, whose integrated report contains highly detailed group-wide sustainability endeavours in the form of a sustainability report, a totally separate document from the annual report. Digital transformation plays a key role in the group's digital transformation, whose milestones in 2022 comprise the optimisation of the digital portfolio through leading data analysis technology, investments in new online solutions for corporate customers, building a data-driven bank and ensuring an enhanced digital experience for clients. The report is structured around the following clusters with their respective material topics: innovation for clients, systemic trends, lean and solid bank, people development, ethics and positive impact on society. The group's business model is centred around the following types of capital: financial, human, social relationship, intellectual and natural, to which several clusters are assigned. This integrated and sustainable business model involves four regions (Germany, Italy, Central Europe, and Eastern Europe) with central structures, with Hungary belonging to the Central European region. The Group's sustainability achievements are also underpinned by data. In 2022, the Group had 8.5 million active digital users, which showed a 6 % rise compared with the year 2021, out of which mobile active users reached 7.2 million, an increase of 11 % compared with 2021. In addition, the Group's banking processes under unified data governance indicated a 20 % point increase, as a result of which it may be regarded as a data-driven organisation (UniCredit, 2022, 53).

*Table 2: UniCredit – Link between digitalisation and sustainability*

| CONCEPTS | CONCEPTUAL RELATIONS | | LINK TO DT | SDGs |
|---|---|---|---|---|
| | CLUSTERS | MATERIAL TOPICS | | |
| DIGITAL TRANSFORMATION | Innovation for clients | Digitalisation and innovation | Increasing bank efficiency | 8, 9, 10 |
| | | Value for clients | Responding to digital challenges in a client-centric manner | |
| CYBER SECURITY | Systemic trends | Cybersecurity | Resilient cybersecurity | 9, 12 |
| FINANCIAL INCLUSION | Positive impact on society | Positive impact on society | Financial education initiatives for the society | 4, 9, 10,17 |
| EMPLOYEE DEVELOPMENT | People development | Employee empowerment | Transforming employees into tech-oriented workforce | 4, 8, 10 |
| | | Diversity and inclusion | Reskilling of employees due to disruptive technologies | |
| | | Future of work | Work-life balance through flexible solutions | |

*Source: Compiled by the author-based UniCredit Group 2022 Integrated Report*

Table 2 only includes those clusters and material topics which are directly associated with the selected concept. Therefore, ethics is a cluster with its material topics, and within Systematic trends, the material topics of climate and environmental impacts, as well as political and social changes, are excluded. Similar to CIB Bank, SDGs 4, 8, 9, 10 show the highest occurrence, followed by SDGs 5, 12 and 17 (Partnership for the goal). Regarding the nature of digital transformation, it is self-explanatory that the materials topics listed show a high resemblance with CIB Bank, although UniCredit explicitly emphasises the importance of education both for employees and society, in terms of which approx. 30 h of training were organised for employees per capita, and 239,400 people groupwide received financial education (UniCredit 2022, 80,93). Digital solutions at the bank also required the development of intellectual capital, which was implemented by recruiting more than 500 tech specialists and organising more than 118,000 h of training dedicated to digital proficiency, as a result of which major cyber incidents dropped by 35 % (UniCredit, 2022, 106, 109).

## 4.3.OTP Bank

OTP Banking Group's 2022 integrated annual report comprises both the Group's Business Report and the Financial Statements. The non-financial statement on the Group's sustainability activities is incorporated into the Consolidated Business Report. In terms of its sustainability approach the Banking Group wishes to, contribute to the following goals to the greatest extent: Quality education (SDG 4), Affordable and clean energy (SDG 7), Decent work and economic growth (SDG 8), Industry, Innovation and Infrastructure (SDG9), and Climate action (SDG 13) (OTP, 2022, 77). However, as Table 3 illustrates, the clusters below do not include the cluster Environmental and social implications of financial products with its material topics Sustainable investments, Green finance and Investments with sustainability endeavours as they cannot be accessed through digital channels. There is only an indirect connection with between them and digitalisation including online promotion and information provided by employees gained through ESG online trainings. The sustainable development goals resemble to a great extent to those of CIB Bank and UniCredit Group. Among the material topics Customer service receives more attention focusing not only on the accessibility of financial services (through digital channels), but also on the online promotion of available products and services. As opposed to CIB Bank, cybersecurity constitutes only a part of ESG governance, which is similar to UniCredit Group, where it belongs to the systemic trends. Employee development also enjoys a high priority.

*Table 3: OTP Bank – Link between digitalisation and sustainability*

| CONCEPTS | CONCEPTUAL RELATIONS- | | LINK TO DT | SDGs |
|---|---|---|---|---|
| | CLUSTERS | MATERIAL TOPICS | | |
| DIGITAL TRANSFORMATION | ESG governance, responsibilities | product development and sales | offering digital solutions through digital channels | 8, 9 |
| | Financial welfare, responsible customer service | accessibility of financial services | remote access through digital channels | 8, 9, 12, 17 |
| | | accessible customer service | website and content editing | |
| CYBER SECURITY | ESG govern. and responsibility | security | overall and cyber security | 9, 12 |
| FINANCIAL INCLUSION | Citizenship | improving financial literacy | training programmes for students and young adults online | 3, 4,11, 17 |

| | | | | |
|---|---|---|---|---|
| EMPLOYEE DEVELOPMENT | ESG governance, responsibilities | HR management | online training for employees | 5, 8 |
| | Responsible employer | career opportunities | transparent career path, job maps available online | 5, 8 |
| | | trainings in compliance, ethics, security, ESG | online | |
| | | safe and healthy work environment | atypical form of working, part-time, remote, hybrid | |

*Source: Compiled by the author based OTP Bank 2022 Integrated Report*

Improving financial awareness regarding banking services, OTP Bank further developed its mobile bank service function called Personal Finance Manager, which was registered for more than 1.7 m. customers groupwide (OTP, 2022, 112). The popularity of digital channels showed a 10 % increase in personal loan applications, reaching an overall 40 %, while the average training time was 35 h/employee (OTP, 2022, 115, 142).

It is apparent that the contextual layout of the three banks shows similarities, as their disclosures are based on clusters comprising material topics and their alignment with the relevant SDGs. Although there is a different designation for clusters, material topics overlap each other in numerous cases. It can also be noted that the designation for the cluster in the case of one bank is regarded as a material topic at another.

Based on the findings, SDGs connected to digitalisation are Quality education (4), whose link to digital transformation is expressed by terms like financial inclusion, spread of financial culture, financial education initiatives for the society, training programmes for students and young adults online; Decent work and economic growth (8), which is traceable by online access to credit, investment in trainings and online education, employee development, increasing bank efficiency, knowledge retention, flexibility of employment, transforming employees into tech-oriented workforce; Industry, innovation and infrastructure (9), which in itself embodies digital transformation through product innovation, digitalisation of services, IT security training for employees, remote access through digital channels, website and content editing; Reduced inequalities (10), which is designated by terms like financial inclusion, spread of financial culture, financial education initiatives for the society, investment in trainings, online education, transforming employees into tech-oriented workforce; Responsible production and consumption (12), which is described service quality offered, online payments and billing, digital customer experience, home banking, remote access through digital channels, IT risk resilient cybersecurity, overall and cyber security; and finally Partnerships for the goals (17), which may be implemented by remote access through digital channels, financial education initiatives for the society, training programmes for students and young adults online. The list above shows a significant overlap between the link to digital transformation and the particular SDGs. As a result, SDG 4, 8 and 10 reveal striking similarities in connection with digitalisation. A similar trend may also be noticed between SDG 9 and 12, while SDG 17 is partially overlapped with SDG 4 and 9. All this may indicate that digital transformation intertwines each aspect of ESG endeavours, although in the case of banks, it is most noticeable with respect to social and governance issues and least so in terms of environmental aspects.

# 5. Conclusions

The paper has revealed that in the case of the clusters and the materiality topics presented, there is a direct link to digitalisation. As the reports of the given banks followed the GRI standards, their content of reporting is very similar to each other. Therefore, sustainability disclosures show a high level of resemblance in terms of their SDGs. However, as the worldview on sustainability of an organisation can be determined through the rhetoric of its sustainability report (Niehoff, 2022), it may be stated that banks' current worldview on digitalisation is predominantly business-centred (weak sustainability) as opposed to regenerative (strong) sustainability. The novelty of the paper lies in the fact that it has pointed out how banks' digital transformation may contribute to the implementation of their sustainability development goals. The research was limited by

the exclusion of the indirect impacts of digitalisation. A further direction of research may involve investigating the environmental component of banks' sustainability endeavours with respect to green finance.

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# AEROSPACE INDUSTRY INITIATIVES AIMED AT AMELIORATING THE ECOLOGICAL FOOTPRINT OF AIRLINES

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**Global aviation companies have increasingly recognised the necessity of addressing their ecological footprint. They have consequently implemented a range of measures with the objective of reducing carbon emissions and promoting sustainable aviation practices. It is of the utmost importance that these efforts are made, given that the aviation industry is a significant contributor to greenhouse gas emissions. Aircraft emissions contribute to atmospheric pollution in multiple ways. During take-off and landing, for instance, aircraft emit pollutants into the lower air layer for approximately 20 min and into the upper air layer for longer periods at altitudes of 10-12 km. Since 1960, the International Civil Aviation Organization (ICAO) has pursued regulatory efforts to govern airborne pollution in proximity to airports, recognising its immediate analogues to vehicular emissions. This study delineates various initiatives indicative of positive strides in fostering environmental stewardship within the aviation sector. However, sustained endeavours and innovative interventions remain imperative for the realisation of enduring sustainability objectives and the mitigation of aviation's environmental footprint.**

## 1. Introduction

Aviation contributes approximately 2.5 % to global carbon dioxide ($CO_2$) emissions. However, when non-$CO_2$ climate effects are incorporated, this proportion escalates to 3.5 %. The elevated levels of atmospheric pollution engender distinctive adverse consequences, particularly attributable to the significant emissions of water vapour from aircraft engines. The resulting water vapour has been demonstrated to exert a substantial warming effect on the atmosphere. Condensation trails, which typically form above 7,600 m under conditions of temperatures below -40 °C and high humidity, result from the freezing of combustion by-products on atmospheric water. These contrails can be discerned from terrestrial vantage points (Varga and Tóth, 2017). The persistence and transformation of contrails into cirrus clouds have significant environmental implications. Although natural occurrences of such clouds are not uncommon, their proliferation has increased markedly over the past century, with aviation activities being the primary contributing factor. The diurnal influence of contrails on climate is characterised by the reflection of sunlight towards Earth during daylight hours, which exerts a detrimental effect on global climate. Conversely, nocturnal contrails impede nocturnal cooling processes, which can also contribute to global warming. Previous estimates have suggested that aviation-induced cirrus clouds contribute an increment of 0.2 °C to global warming (Rohács, 1994). The number of air passengers worldwide first exceeded 500 million in the early 1970s, subsequently increasing at a gradual rate until the turn of the millennium. In 2000, nearly 1.7 billion passengers opted for air travel. Subsequently, the market experienced a downturn, initially in the aftermath of the terrorist attacks of 11 September 2001 and subsequently in the wake of the global economic crisis in 2008. However, it demonstrated a rapid recovery. In 2019, a total of 4.5 billion passengers utilised airports across the globe. The restrictions imposed in response to the global pandemic caused a significant decline in the number of air passengers, with the figure falling below two billion in 2020 (ICAO, 2022).

As indicated by World Bank surveys, individuals residing in the least developed and low-income countries (47 LDCs in 2024) utilise air transportation at a negligible rate. It is notable that residents of higher-income countries are the most frequent flyers. However, it would be beneficial to observe the flying habits of people in middle-income countries. Until the 1990s, the number of people in these countries travelling by air remained at a very low level. In the early 2000s, however, there was a marked increase in the number of middle-income country residents travelling by air. The number of people in middle-income countries using air transport increased twofold over a 7 y period, reaching 500 million in 2006. By 2012, after another 6 y, it had doubled again to over 1 billion. The last year in which there was a notable increase in air travel was 2019 when the number of passengers exceeded 1.8 billion (World Bank, 2022). The increasing demand for travel has resulted in the expansion of air services. The number of available destinations has increased, and the popularity of low-cost airlines has been uninterrupted since the early 1990s. These airlines offer low-cost flights with a reduced level of service compared to economy class. In 2020, the global pandemic caused a significant reduction in the number of people travelling by air, with the number of flights falling to 16.9 million. Following the lifting of pandemic-related restrictions, the number of flights increased markedly in 2021, reaching 20.1 million. This figure rose further to 27.8 million in 2022 before experiencing a substantial surge in 2023, with 36.8 million aircraft taking to the skies. The industry is now exhibiting signs of robust growth, with an estimated 40.1 million flights forecast for 2024 (Statista, 2023). The sustained expansion of the airline industry gives rise to considerable sustainability-related challenges. The growth in aviation data, including an increase in flight and passenger numbers, directly contributes to a rise in carbon emissions, which have a detrimental impact on the environment. Other pollutants emitted by aircraft, such as nitrogen oxides, have an additional detrimental impact on air quality and contribute to climate change. In order to achieve sustainable air transport, innovative solutions are required, including the development of more fuel-efficient aircraft, the use of biofuels and the optimisation of air traffic management. Currently, it is no longer sufficient for airlines to be the most competitive in terms of passenger numbers; they must also demonstrate responsible and sustainable operations.

# 2. The role of aviation in environmental pressures

The air transport sector is experiencing rapid growth, yet it also presents significant environmental concerns. The air pollution generated by the industry represents a significant contributor to the emissions of carbon dioxide and other pollutants that degrade air quality and exacerbate global climate change. The noise pollution generated by aircraft has a detrimental impact on the well-being of individuals residing in proximity to airports, as well as on wildlife. The quantity of waste produced during flights, particularly in the form of single-use plastics and other materials on board, represents a considerable environmental burden. It is imperative that environmentally friendly technologies and practices be introduced with the aim of enhancing the sustainability of the aviation sector.

## 2.1. Atmospheric pollution

In favourable conditions, contrails from aircraft can persist in the atmosphere as contrail cirrus, which are ice clouds that can retain heat within the Earth's atmosphere. The impact of contrail cirrus on the climate has been largely overlooked in global initiatives to offset aviation emissions, despite the fact that contrail cirrus has contributed more to the warming of the atmosphere than all $CO_2$ emitted by aircraft since the inception of aviation. A recently published study in the European Geosciences Union (EGU) journal Atmospheric Chemistry and Physics has revealed that the climate impact of contrail cirrus will be significantly amplified as a consequence of increased air traffic activity, with a projected tripling by 2050 (EGU, 2019). The aviation sector presents a significant challenge in terms of decarbonisation. While electricity, renewables and nuclear power are facilitating the transition to low-carbon road transport and heating, and low-carbon alternatives are emerging for the cement and steel industries, aviation is lagging behind in this regard. It seems inevitable that global demand for aviation will increase in the coming decades as populations become richer. The growth in emissions will depend on the sector's ability to sustain energy efficiency improvements and switch to low-carbon fuels, where little progress has been made so far. While more efficient aircraft can reduce emissions growth, it is clear that to eliminate it completely, the sector will need to switch to electrification, biofuels, hydrogen or a combination of these. Until this transition is achieved, aviation will represent a significant environmental burden (Griffiths et al., 2023). The overall impact of aviation on global

warming can be quantified by the so-called "radiative forcing". The radiative forcing metric quantifies the discrepancy between the energy received and the energy radiated back into space. Should the quantity of energy absorbed exceed that radiated, the atmosphere will consequently become warmer. Some authors (Lee et al., 2021) posit that aviation is responsible for 3.5 % of the radiative forcing, whereas another study (Klöwer et al., 2021) asserts that aviation is responsible for 4 % of the global temperature rise.

## 2.2. Impact of aircraft noise pollution

In addition to the issue of air pollution, the phenomenon of noise pollution from aircraft represents a significant challenge. Sound waves are generated by a number of factors, including the operation of engines and other aircraft equipment, the loading of structural components and the turbulence of the air around the aircraft. These sound waves are collectively referred to as aircraft noise. The noise levels in the vicinity of airports are subject to continuous monitoring at designated measurement points. These are employed in the production of so-called noise contour maps, with each zone classified according to the decibel level of aircraft noise. Given that aircraft noise is not constant throughout the day, a measure called $L_{den}$ is employed to quantify the combined noise characteristics of daytime and nighttime. A distinct metric is employed to quantify noise levels during nocturnal hours: the $L_{night}$ metric is utilised to represent the noise characteristics between 22:00 and 06:00 (Palik and Csermely, 2013).

In Europe, aviation noise represents the third largest source of noise, after road and rail traffic. A 2017 UN study revealed that 3.2 million people in the continent are affected by aircraft noise ($L_{den}$ above 45 dB), with 1.4 million individuals experiencing severe sleep disturbances as a consequence. Sufficient, undisturbed sleep is a prerequisite for optimal daytime alertness and performance, quality of life, and health (Fritschi et al. 2011). In order to mitigate the adverse effects of noise pollution, airports and government agencies have implemented a series of measures, including night flight restrictions, noise quotas, optimised flight procedures and public window sealing competitions. Airlines are attempting to address the issue primarily by utilising more contemporary aircraft with quieter engines. The mean noise level of aircraft has been declining for several years. The area affected by noise levels exceeding 80 dB during the take-off and landing of a 75-t jet aircraft was 63 km² in 1977. However, this has decreased to 24 km² in the present day. It is anticipated that the noise energy generated will be further reduced within two decades thanks to the advent of more modern engines. However, it is also acknowledged that air traffic is expected to increase until 2040, which will result in an overall minimal reduction in noise pollution (EASA, 2022).

## 2.3. In-flight waste and wastage

The issue of aviation waste is less significant than that of air and noise pollution. Nevertheless, a considerable quantity of waste is produced by those travelling by air. A considerable proportion of this is composed of plastic. A considerable proportion of this substantial quantity of waste could be recycled; however, 91% of it is either incinerated or disposed of in a landfill. In many instances, this is due to the lack of dedicated collection facilities provided by airports.

A study conducted by the International Air Transport Association (IATA) has estimated that the aviation sector generated 3.6 Mt of cabin waste in 2023. Based on current projections for passenger growth, this waste volume is expected to double by 2040. The elevated figures are primarily attributable to the practice of airlines packing food items as closely together as possible when providing catering services. This is done for reasons pertaining to hygiene, safety, and practicality (e.g., to avoid the need for washing up). On longer flights, utensils distributed to passengers are placed in disposable packaging. In the course of cabin cleaning, a range of materials is collected, including newspapers, magazines, textiles (such as headrest covers, blankets and cushions), equipment bags, headphones and drinks bottles (including full bottles). The cleaning personnel will place all waste items into plastic bags. Furthermore, the waste stream includes small quantities of food discarded on the floor or placed in the pockets of seat backs, as well as food items brought on board by passengers. The majority of food waste is generated as a result of the provision of in-flight meals and beverages by cabin crew. A survey conducted by the International Air Transport Association (IATA) revealed that 20 to 30 % of all waste originates from food and drink items. It is policy that any remaining food must be discarded upon landing. Additionally, staff are able to collect any recyclable materials that have been separated separately, including paper, aluminium cans and plastic bottles. The responsibility for the

disposal of catering waste falls upon the cleaning contractor. A survey conducted by the Aviation Sustainability Forum and supported by IATA in early 2024 revealed that, of the waste generated on 25 international flights arriving at Singapore Changi Airport, 85 % was food waste, and 15% was cleaning waste. The average weight of waste per passenger was 0.94 k (IATA, 2024).

# 3. The environmental efforts of airlines

On 30 July 2024, Air New Zealand announced that it would be unable to meet its 2030 emissions reduction target date and revoked its commitment. The company has stated that it requires sustainable fuel and new aircraft in order to meet its commitment. In 2022, the company committed to reducing its emissions by a minimum of 29% by 2030 compared to the then-current level. The company cites external factors as the primary drivers behind this decision. In order to meet their target, they require access to more fuel-efficient aircraft manufactured by external parties. Additionally, they must facilitate the increased availability of environmentally friendly and sustainably produced fuels. According to Air New Zealand, there are delays in both of these conditions across the aviation industry (da Silva, 2024). It would be beneficial to examine the measures that airlines can implement in order to fulfil their commitments. In addition to the acquisition of more efficient aircraft types, the industry must address the challenge of making existing aircraft more efficient. The optimisation of operational procedures and the utilisation of alternative fuels and carbon offsets may prove to be among the most effective solutions.

## 3.1. Acquisition of more efficient aircraft types

In Europe, low-cost airlines endeavour to maintain the average age of their aircraft at a minimum. In addition to fuel efficiency, this approach results in notable cost savings due to a reduction in the frequency of aircraft breakdowns. The average fleet age of Wizz Air is 5.4 y, while Ryanair and EasyJet have an average fleet age of approximately 7-8 y. The largest European-based airlines, including Lufthansa, Air France-KLM, SAS, and others, have an average fleet age of between 10 and 13 y (Airlinefleet.net, 2024). Each of these airlines utilises two distinct aircraft types, namely the Boeing 737 and the Airbus A320. In the preceding decade, manufacturers have introduced lower-emission versions of these aircraft types. Ryanair characterises the new aircraft as a “game changer”, indicating that it is anticipated to bring significant enhancements in efficiency. The new aircraft is equipped with LEAP-1B engines manufactured by CFM International. According to Ryanair’s 2023 Sustainability Report, this will result in a 20 % reduction in fuel consumption per seat and a 50 % reduction in noise emissions compared to the previous type. Additionally, the Lden noise footprint is expected to be reduced by approximately a quarter (Ryanair Sustainability Report, 2023). EasyJet and Wizzair operate the Airbus A320 family and have placed many orders for the new NEO (New Engine Option) aircraft. These are powered by Pratt & Whitney engines, and the new technology has resulted in a 20 % reduction in fuel consumption, a 50 % reduction in nitrogen oxide emissions and a 50 % reduction in noise emissions compared to previous generation aircraft (Easyjet Sustainability Report, 2023 and Wizzair Annual Sustainability Report, 2023).

## 3.2. The enhance of the efficiency of existing aircraft.

It is becoming increasingly evident that a multitude of developments can facilitate immediate reductions in consumption. Consequently, it can be argued that airlines have a more significant role to play than aircraft manufacturers, given that the majority of development and testing is now conducted by airlines themselves on their aircraft. Furthermore, airlines have reported that by washing and cleaning engines more frequently than the average, they have observed reductions in consumption of up to 0.5-1% (NASA Spinoff 2010). A winglet is defined as a vertical auxiliary wing located at the extremity of the wings. A well-designed winglet serves to mitigate the turbulence that can occur at the wingtips, which can otherwise result in drag and, consequently, energy loss. In 2021, the Portuguese airline HiFly announced the TRINITAIR, a joint development with The Mirpuri Foundation and The Aircraft Performance Company GmbH. This device is a special wingtip that branches in three directions, similar to the plumage of a bird. The resulting three protruding wing tips are oriented as follows: one pointing upwards, one slightly upwards, and one slightly downwards. The manufacturer asserts that the new winglet can reduce fuel consumption by 2 %. Another significant advantage is that it can be retrofitted to the aircraft in less than a day. Calculations have demonstrated that an Airbus

A330 aircraft flying from Frankfurt to Hong Kong can save at least 1.2 t of fuel as a result of utilising the TRINITAIR winglet (HiFly, 2021). In 2022, BASF and Lufthansa Technik collaborated to install anti-friction film on ten Boeing 777 freighter aircraft operated by the airline. The coating, designated AeroSHARK, exhibits a surface texture analogous to the ribbed skin of sharks, contributing to a reduction in friction. The ribs, which are 50 µm in height and barely visible to the naked eye, are parallel to the airflow and serve to reduce friction. When applied to the wing-neck, they increase lift. The material is notably lightweight, with a density of only 180 g/m$^2$ of film. The technology has the potential to reduce fuel consumption by 0.8 % in a Boeing 777 aircraft. It is asserted that this equates to a reduction of approximately 3,700 t of kerosene and 11,700 t of carbon dioxide emissions on an annual basis. Tests and measurements demonstrate that if the technology were to be installed on 24,000 aircraft globally, it would result in the saving of 2 Mt of kerosene and 6.3 Mt of carbon dioxide emissions on an annual basis (Lufthansa Technik, 2022).

## 3.3. The optimisation of operational procedures and the utilisation of alternative fuels

The optimisation of operational procedures in the aviation sector is a process that aims to enhance efficiency in order to reduce fuel consumption and emissions. This encompasses enhanced flight planning, the optimisation of flight routes, the reduction of aircraft weight and the improvement of air traffic control. Techniques such as continuous descent approaches, single-engine taxiing and more precise take-off and landing procedures will assist in the reduction of fuel consumption. These measures not only result in cost savings but also lead to a notable reduction in the environmental impact of the industry, enhancing the sustainability of operations.

The utilisation of alternative fuels, such as sustainable aviation fuel (SAF), represents a pivotal strategy for the reduction of the carbon footprint of the aviation sector. However, this approach does not offer any financial benefits to airlines. The use of sustainable kerosene (obtained from biomass, waste oil or other sustainable sources) in aircraft also results in increased costs, which are ultimately borne by passengers. It is for this reason that airlines are petitioning policymakers to implement regulations that will facilitate the adoption of sustainable kerosene as soon as is feasible. Given that this is not a viable long-term environmental measure, the advent of hydrogen or electric propulsion could eventually bring about a significant enhancement in the sustainability of aviation. It will take years before the first new types of aircraft are introduced and even longer before they become widely available on the market (SkyNRG, 2024).

## 3.4. Carbon offsetting

In 2016, the International Civil Aviation Organization (ICAO) and the United Nations body responsible for aviation policy developed the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), which aims to offset carbon dioxide emissions from civil aviation. The objective of the scheme is to stabilise the carbon dioxide emissions of airlines at the 2019 level from 2021 onwards through the implementation of various offset programmes. It is anticipated that participation in the scheme will be voluntary until 2026, after which it will become mandatory for all countries and airlines, with a few exceptions. Once an airline has joined the scheme, it will be required to monitor and offset its emissions. The objective is to achieve $CO_2$ reductions equivalent to the amount of carbon dioxide emitted by the airlines in question elsewhere in the world. Such reductions may be achieved through afforestation projects, renewable energy investments, or energy efficiency improvements, for example. The financial resources required for the implementation of these projects are sourced from the purchase of carbon credits by either passengers or airlines. While carbon offsetting schemes can be an effective means of reducing carbon emissions, they have also been the subject of criticism. It is argued that such measures permit airlines to circumvent genuine emission reduction strategies while, at the global level, emissions remain unaltered. One criticism of the CORSIA programme is that it is voluntary in its initial phase, which may limit its effectiveness (Kaplan et al., 2023).

# 4. Conclusions

The objective of airlines to decarbonise air transport by 2050 represents a significant and ambitious undertaking, one that is indisputably necessary in the fight against global climate change. Nevertheless, the target and its implementation plans have been subjected to a number of critiques that call into question both its credibility and its practical feasibility. One of the principal criticisms pertains to the technological feasibility of the proposed solution. At the present time, no technology is available that would allow for the complete elimination of carbon emissions in the context of air transportation. The development of electric aircraft is still in its infancy, and although the technology shows promise, it is not yet capable of flying long distances or carrying large numbers of passengers efficiently. Alternative fuels, such as sustainable aviation fuel (SAF), are currently costly and not available in sufficient quantities to meet the global aviation industry's needs. The attainment of carbon neutrality will necessitate substantial investment in both research and development and infrastructure alterations. However, many airlines and governments are not exhibiting the requisite financial and political commitment to achieve the desired outcomes. Despite the introduction of green programmes and the use of sustainable aviation fuel (SAF) by some airlines, these initiatives appear to be more akin to marketing ploys than genuine systemic transformations. Certain actors within the airline industry persist in lobbying for the relaxation of environmental regulations, which is contrary to the objective of carbon neutrality. The carbon offsetting schemes employed by airlines are more likely to be greenwashing, as they frequently do not result in genuine emission reductions. Additionally, such schemes do not provide sufficient incentives for technological innovation or structural changes, which are essential for achieving carbon neutrality by 2050. Although airlines are promoting carbon neutrality, the aviation industry is striving for continued growth. As demand for aviation continues to increase, it is challenging to envisage a scenario in which emissions will decline significantly. The incongruity between the industry's growth model and its carbon neutrality targets gives rise to questions concerning the extent to which airlines are genuinely committed to climate protection. It is also important to acknowledge that the majority of carbon emissions from aviation are generated by countries with higher levels of wealth and by individuals with more frequent travel patterns. Nevertheless, the financial burden of pursuing carbon neutrality targets frequently falls disproportionately on less affluent countries and communities, which often possess fewer resources to adapt to these changes. It is imperative that measures to achieve the aforementioned carbon neutrality objectives are fair and equitable. Although the 2050 carbon neutrality target is commendable and imperative, the route to its attainment is beset with challenges and contradictions. The feasibility of achieving the target is contingent upon overcoming a number of significant obstacles, including technological, financial and political barriers, the desire for growth, and criticisms of carbon offset schemes. In order for the aviation industry to become genuinely sustainable, it is imperative that radical and systemic changes that extend beyond the scope of current strategies and ambitions are implemented.

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# THE IMPACT OF DIGITAL SERVICES DEVELOPMENT ON SUSTAINABILITY FOR LAST-MILE DELIVERY

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The aim of this paper is to show the impact of the COVID-19 epidemic on the quality of life, the development of internet networks and the development of various e-services in order to examine how it affects last-mile delivery processes. In this context, the paper examines the impact of COVID-19 on the market for online services in Central European countries. Within the framework of the primary research, the knowledge background is visualised using Vosviewer, presenting the keywords used for searching and the number of results that were narrowed down. The secondary research will then map the extent of digitalisation development, with a particular focus on Hungary's development in relation to other countries in terms of e-commerce. The research questions addressed in this paper are: how e-banking and e-commerce services have evolved over the last 5 years and whether COVID-19 has had an impact on the pace of development of digital services. Finally, the implications of the growth of e-commerce from a sustainability point of view, with a particular focus on its logistical aspects, and the possible solutions to overcome this problem are presented, as well as the advantages and disadvantages of the proposed solutions. This study is unique in its approach to integrating digitalization and sustainability within the last-mile delivery sector, emphasizing the challenges and opportunities that have arisen post-COVID-19. By focusing on Central European data, specifically Hungary, this paper offers a novel perspective that addresses both regional and industry-specific needs for sustainable last-mile delivery solutions.

## 1. Introduction

Over the past five years, digitalisation has developed rapidly, which has been significantly accelerated by the COVID-19 pandemic. The pandemic has forced a significant part of the world's population into home isolation, and the internet and e-services have become an important part of everyday life. This digital revolution has brought with it many positive and negative effects. In this article, the study focus on how the COVID-19 pandemic has affected living standards, internet networks, and the development of various e-services. The aim of thesis this article is to show how the COVID-19 pandemic has affected everyday life, especially in the field of Internet and e-services. The study will examine how the demand for the internet and e-services has increased, how living standards have changed in the online world, and what developments and changes have taken place in the field of digitalisation. In addition, the paper presents what research questions it seeks answers to and what methods it uses during the analysis. How has the COVID-19 pandemic affected e-commerce and internet use? How has the pandemic affected living standards in the digital space? What developments have been made in Internet networks and e-services in the last 5 years? What long-term changes could the COVID-19 pandemic bring to digitalisation? The novelty of this research lies in its comprehensive assessment of digitalization's impact on sustainability in last-mile delivery. While existing studies often examine digitalization and e-commerce growth independently, this study uniquely addresses their

convergence and the resulting sustainability challenges. This research provides a systematic framework for identifying risks and potential solutions specific to last-mile delivery within a Central European context. This approach contributes a fresh perspective to the ongoing discourse on sustainable digitalization and e-commerce logistics, emphasizing the need for regional solutions.

The methodology of the article is literature analysis based on available sources in order to map developments in the field of digitalization and e-services. The article also uses data for secondary research, such as surveys and interviews with stakeholders, to better understand the impact of the COVID-19 pandemic on living standards and the digital world. This paper analyses in detail the impact of the COVID-19 pandemic on e-commerce and internet networks. First, the study presents the impact of the pandemic on living standards, especially the changes in the online space. After that, analyse developments such as teleworking, online education, grocery delivery, healthcare services and e-commerce in detail. Based on the results of literature analysis and primary research, the article explores to what extent digitalization has become a driver of sustainability, while contributing to energy savings and more efficient management of infrastructure. In addition, the study addresses the social and environmental challenges of digital technologies and identify areas where further research is needed.

## 2. Literature review

Digitisation is a mechanism by which analogue information, such as images, sounds or writing, is converted into digital format. As a consequence, information can be stored, processed and shared using computers or electronic devices. According to the latest data for 2019, Hungary is among the EU leaders in terms of internet access, with internet penetration around the EU average, while in other areas it is in the bottom third and 22nd overall among EU countries (Eurostat, 2022). The data below is based on the DESI index, measured by the index score, which is an absolute number. Index scores indicate the digital development of each country, with higher scores indicating a more developed digital environment (Ghazy et al., 2022). In general, these scores are not provided with a unit of measurement because they show relative values in comparisons between countries. The spread of smartphones and mobile internet access has enabled more and more people to benefit from the web. In many areas where traditional computer access was limited or even expensive, individuals can now access the internet more easily via their mobile devices. The spread of 5G networks has also led to significant advances in the speed and availability of the web (Yu et al., 2023). These faster networks allow faster downloading and streaming of vast amounts of content, such as videos and games.

In the figure below, using the Eurostat (De Araujo and Reinhard, 2015) page, the study has mapped internet usage data for the last 6 y before the COVID-19 epidemic and how it evolved during and after the epidemic (Eurostat, 2022). All this for the Central and Eastern European countries. From this, it can seen that there has been a steady dynamic growth in almost all countries every year, but there is no spike due to the epidemic as expected before the research. This is precisely why we will dig deeper into the subject and find that there were big changes in other, more exciting areas. The data are households as a percentage. Data for 2023 are not yet available, so the study has examined data up to 2022 for all Eurostat tables. During the epidemic, the demand for internet connections increased due to the rise in online activities, as well as working from home. This placed a higher load on Internet infrastructures, and, as a consequence, Internet and e-service providers had to make considerable efforts to ensure reliable connections. Many ISPs and eSPs have made significant investments to expand their infrastructures. The objective was to provide reliable and faster Internet connections to meet the growing demand (Lyu et al., 2023). The impact of the coronavirus epidemic on the overuse and spread of digital platforms has been enormous, as individuals around the world have been forced into isolation at home and the online world has become a major means of contact and entertainment. The study describes this process below (Elshaer et al., 2024). The epidemic has led many companies and schools to switch to teleworking and distance learning. Platforms such as Zoom, Microsoft Teams, in addition to Google Meet have grown rapidly as individuals have participated in online meetings, video conferences, in addition to online classes.

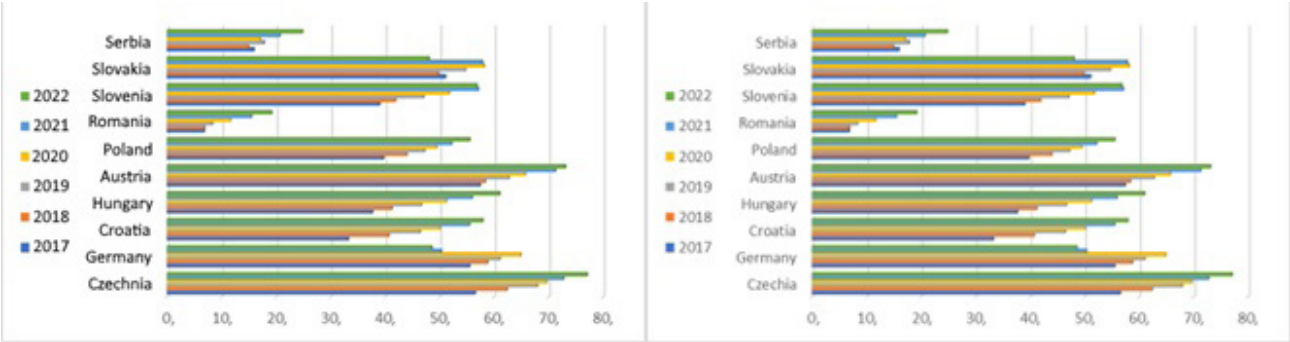


*Figure 1: Internet usage change [Eurostat 2022]*

Despite the rapid advancements in digital services and e-commerce during the COVID-19 pandemic, there is limited research that specifically addresses the intersection of digitalization and sustainability in the last-mile delivery sector, particularly within the context of Central Europe. Most existing studies focus either on the digital transformation of e-commerce or on broader sustainability challenges, but few analyze how digital services can support sustainable last-mile delivery. This paper aims to bridge this gap by examining the role of digitalization in overcoming last-mile delivery challenges and exploring its sustainability implications. By focusing on Hungary as a case study, this research highlights regional trends in digitalization and presents insights relevant to other Central European countries facing similar logistical and environmental challenges.

# 3. Methodology

This research employs a mixed-methods approach that combines primary and secondary research to assess the impact of digitalization on sustainability in last-mile delivery. The primary research utilizes VOSviewer to visualize and analyze the keywords and patterns associated with the relevant literature, allowing for a comprehensive mapping of the current knowledge landscape. For secondary research, statistical data from reliable sources, such as Eurostat, are analyzed to compare digitalization trends across Central European countries, with a particular focus on Hungary's e-commerce sector.

# 4. Analysis

For the analysis of the topic, first searched the Science Direct database for publications from the last 5 years using keywords related to the topic, and then analysed the resulting databases using Vosviewer (Jan van Eck & Waltman, 2023). The Vosviewer program shows the degree of co-occurrence of keywords, i.e. it provides an overview of the research published on the topic.

| Results of ScienceDirect on 25/03/2024 - Last 5 years (2019-2024) | | | | | | Total |
|---|---|---|---|---|---|---|
| Digitalization | Development | | | | | 335,827 |
| Digitalization | Development | "Internet access" | | | | 4,746 |
| Digitalization | Development | "Internet access" | E-bank | | | 857 |
| Digitalization | Development | "Internet access" | E-commerce | | | 740 |
| Digitalization | Development | "Internet access" | E-bank | COVID-19 | | 342 |
| Digitalization | Development | "Internet access" | E-commerce | COVID-19 | | 281 |
| Digitalization | Development | "Internet access" | E-bank | COVID-19 | "Last mile delivery" | 6 |
| Digitalization | Development | "Internet access" | E-commerce | COVID-19 | "Last mile delivery" | 9 |
| Digitalization | Development | COVID-19 | "Last mile delivery" | | | 229 |

*Table 1: Summary of ScienceDirect keyword search results (25/03/2024)*

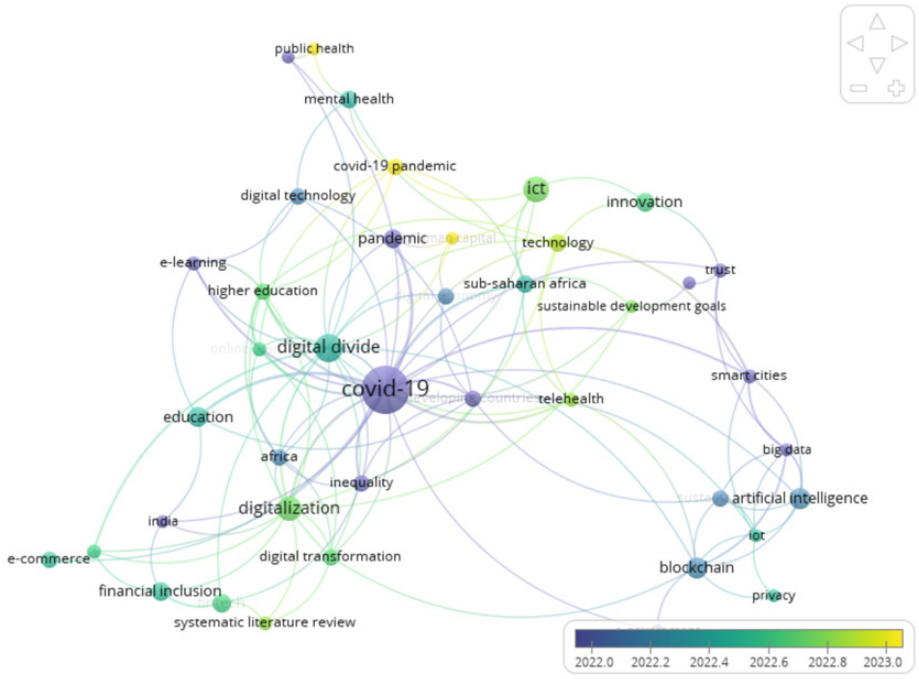


*Figure 2: Visualisation of the keywords Digitalization, Development, Internet Access, E-bank and Covid-19 based on the Science Direct database (25/03/2024)*

As you can see in Table 1, I chose the words Digitalization and Development as the starting words for my research, which got 335,827 hits in the Science Direct database. Then, we narrowed down the hits, first using the term Internet access, which was also examined over the last 5 years. The study found that more than half of the publications obtained for these keywords were written in the last 5 years. As the development of digitisation "spiked" significantly during the COVID-19 epidemic, further narrowed down the keyword COV-ID-19, which showed that a significant proportion of publications were written in relation to the epidemic.

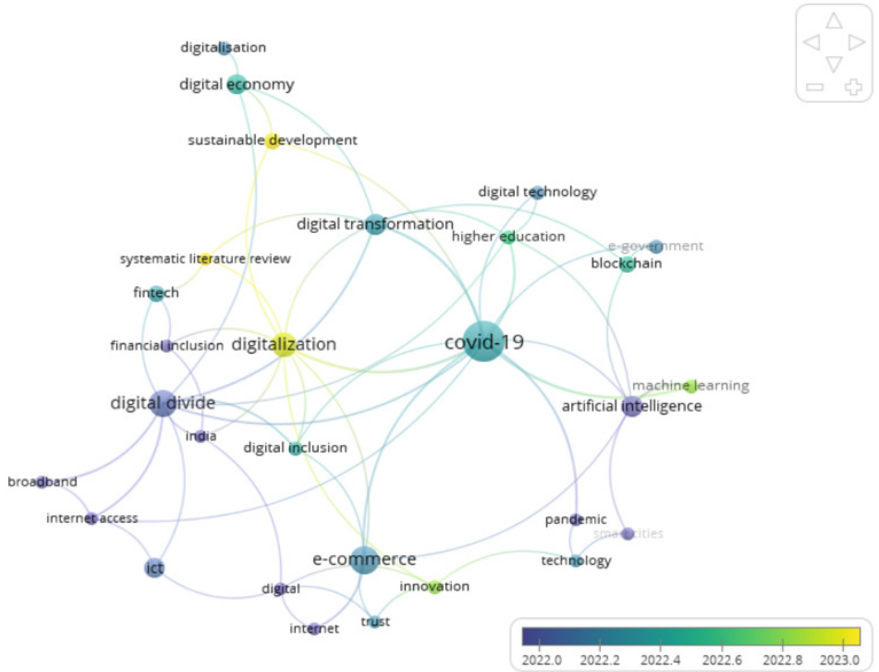


*Figure 3: Visualisation of the keywords Digitalization, Development, Internet Access, E-commerce and Covid-19 based on the Science Direct database (25/03/2024)*

The study then looked at the initial vocabulary by adding the words e-banking and e-commerce, with a particular focus on the last 5 years, after; Table 1 we can see that the evolution of digitalisation has also occurred in relation to e-services. First, the figure presents a visualisation of the database of publications obtained for the keywords Digitalisation, Development and E-banking using Vosviewer in Figure 2. In the Vosviewer setup, the minimum number of occurrences of a keyword was set to 4 in order to visualize the strength of co-occurrence of keywords properly. As can be seen in Figure 2, the Innovation and Blockchain keywords were the focus for the given keywords in mid-2020. However, in 2022, the focus has shifted to the keyword COVID-19, and the keywords Circular Economy and Sustainability have also appeared, suggesting that the E-bank service supports the achievement of sustainability.

Figure 3 is based on a database obtained from the keywords Digitalization, Development, and E-commerce. As can be seen in the figure, the focus in 2019 was on the keywords Globalisation, Internet and Supply chain management, for 2022 there is also a strong focus on COVID-19, and here also, the keywords Circular economy and Sustainability are visible, indicating that the impact of E-commerce on sustainability was investigated in relation to the development of the E-commerce service. The keywords Machine learning, Cyber Security and Technology adoption are also visible, i.e. a set of additional areas supporting digital services in relation to the development of digitalisation. Overall, the review of the publications leads me to conclude that the COVID-19 epidemic has had a significant impact on the development of e-services, which is reflected in both E-banking and E-commerce.

Figure 4 is based on a database obtained from the keywords Digitalization, Development, Last-Mile Delivery and Covid-19. The minimum number of occurrences of the keyword in the Vosviewer setting is 4. As can be seen in the figure, the number of scientific publications found is 229; thus can call this a "research gap", so it can be concluded that there is relevance to the preparation of the article. Overall, by reviewing the publications, the study concludes that the COVID-19 epidemic has had a significant impact on the development of e-services, and therefore, the volume of delivery has increased, and the resulting CO2 emissions have increased greatly. Thus, the impact of digitalisation on sustainability needs to be investigated. E-commerce, or online commerce, has undergone significant change over the last 5-10 years and is constantly evolving. Below, you will find some of the most significant changes and trends.

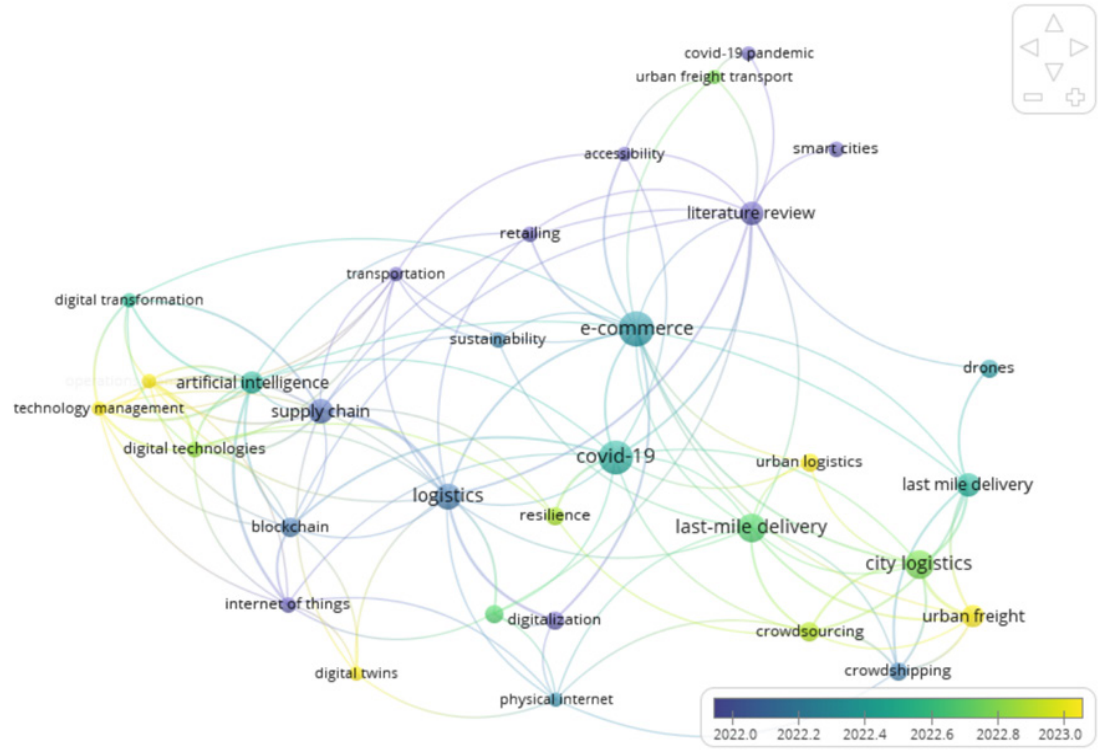


*Figure 4: Digitalization, Development, Last-Mile Delivery, Covid-19 keywords visualization based on Science Direct database (25/03/2024)*

The proliferation of smartphones and tablets has led to individuals increasingly shopping online with the support of their mobile devices. The key to e-commerce has been the development of simple as well as user-friendly mobile apps as well as websites (Chundakkadan & Sasidharan, 2023). With the spread of teleworking, demand for computing instruments, such as laptops and peripherals, has increased, and sales of home office equipment, such as desks and chairs, have also risen. Individuals have increasingly chosen online pharmacies in addition to health products to purchase medicines in addition to health care products. During the COVID-19 epidemic, online shopping and e-commerce have grown significantly, making home delivery a priority in the recent periods and its popularity has continued after the epidemic. Customers expect to receive their products quickly, accurately and cheaply. The final element of the delivery process is Last-Mile Delivery, which is the last phase of the delivery process, i.e. the delivery from the shops or logistics centres to the customer's door (Sós et al., 2023). Efficiency and speed are key elements of Last-Mile Delivery (Bartucz et al., 2023), i.e. the couriers delivering the goods want to do their job as quickly and efficiently as possible. Therefore, delivery people periodically revise the routes suggested by the route planner. Their decision may be motivated by their dislike of a particular route, for example because of the risk of constant traffic congestion (Balassa et al., 2023). The route may also be changed based on information provided by the customer, for example, requesting delivery to a different address than the one indicated in the address on the day of delivery, but to a different address not indicated in advance. In this case, it is necessary to revise the routing offer again in order to work efficiently. The impact of the development of digitalisation on sustainability has been researched by a number of experts (Kunkel and Tyfield, 2021), as the development of digitalisation has a significant impact on sustainability. With the development of technology and the spread of the internet, there are a number of benefits that contribute to promoting sustainability, but also challenges. In the following, will be describe how digitalisation is impacting on sustainability. Digitalisation contributes to increasing energy efficiency, which reduces energy consumption and its impact on the environment. For example, more efficient use of energy in computers and data centres and the use of renewable energies have a positive impact on reducing greenhouse gas emissions (Bosona, 2020). Some of the stores have been converted into online shops, reducing energy use (heating, lighting). On the other hand, a significant proportion of digital services have switched to digital invoicing, which has reduced the amount of paper used and the amount of material used for printing, and has also reduced costs. Digitalisation and increased energy efficiency allow for reduced energy use, which helps to reduce the carbon footprint and greenhouse gas emissions (Kunkel & Tyfield, 2021). The increase in the number of online shops has put a strain on the supply chain. On the one hand, there were many more parcels to be delivered, which meant more goods vehicles on the road, and on the other hand, there were significant delays in parcel delivery. However, it was not only orders that put pressure on the supply chain (Correia et al., 2021), but also back-orders (Almelhem et al., 2023), the number of which increased significantly during the COVID-19 epidemic, but even today a small proportion of orders still 'travel' as back-orders. Conclusion

The last five years have seen a rapid development of digitalisation, accelerated by the coronavirus epidemic. The web and e-services have become an integral part of everyday life. As a consequence of the coronavirus epidemic, there have been a number of negative changes, but also some positive ones, for example, in terms of digitisation. E-commerce, online education, grocery delivery, and health services have all expanded. The development of digitalisation can contribute to profitability by increasing energy efficiency, managing infrastructures more efficiently and increasing the availability of profitable products. However, it is relevant to consider the environmental and social challenges of digital technologies, such as e-waste, as well as data protection issues. The combined impact of digitalisation and the coronavirus epidemic is fundamentally transforming our daily lives and our economy, and it is also relevant to take good measures in the interest of a profitable and responsible digital future. The paper will show the impact of the digital revolution on our lives and highlight the key issues that society and businesses need to address as a result of the ongoing evolution of digitalisation and the impact of the epidemic. Addressing the challenges and alternatives ahead is key to profitability and prosperity.

While this study provides valuable insights into the intersection of digitalization, sustainability, and last-mile delivery, several limitations must be acknowledged. First, the analysis focuses primarily on Central Europe, specifically Hungary, which may limit the generalizability of findings to other regions with different digital infrastructure and regulatory environments. Additionally, the study relies on secondary data for some analyses, which introduces potential limitations in data accuracy and completeness. Future research could expand on this work by incorporating data from a wider range of regions, allowing for cross-country comparisons.

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# APPLICATION OF ARTIFICIAL INTELLIGENCE IN AEC – FOCUSING ON SUSTAINABILITY

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**In the era of digital transformation, the role of artificial intelligence (AI) is increasingly prevalent in the Architecture, Engineering, and Construction (AEC) sector. With the emergence of AI capable of text generation, the AEC industry is actively seeking opportunities for its application, leading to the development of specialised software for various tasks to facilitate automation. Following the literature, this article presents the evolution of artificial intelligence and its key characteristics. Furthermore, the study explores the potential applications of AI in the AEC sector, categorising different solutions based on their intended use and delving into their applicability, usability, and key values. The article presents solutions available in text generation, image creation, design optimisation, sustainability and simulation, and within the field of Building Information Modeling (BIM). In addition to these possibilities, the article focuses specifically on analytical solutions and provides a more detailed insight into their functioning. After outlining the possibilities, it discusses the integration of AI into the design process. The article highlights notable examples of the rising popularity of AI in the construction industry and discusses their utility in various stages of the design process.**

## 1. Introduction

In today's dynamic world, artificial intelligence (AI) has become increasingly accessible. AI is transforming industries, businesses, and our daily lives in unprecedented ways. While the significance of AI continues to grow, there remains considerable scepticism regarding its practical application. Common misconceptions, such as its complexity, costs, and accessibility, often result in missed opportunities for exploring its potential. In reality, AI is becoming easier to use, more affordable, and one of the defining trends of our time. Nowadays, AI is available through cloud services, meaning businesses do not need to invest in hardware or software to utilise it. This makes AI more accessible and affordable for businesses of all sizes.

Several AI systems trained on large datasets are also available through APIs. AI APIs are software interfaces that enable businesses to integrate AI into their existing applications. This simplifies the use of AI for businesses without the need to write their own code.

Moreover, numerous AI tools are now available, focusing on various aspects of life. Examples include Microsoft Edge with Copilot and Bing, as well as Google Chrome with Bard AI and Gemini. These tools are designed to make AI easier to use and more accessible to everyone interested.

## 2. Literature Review and Research Methodology

A comprehensive literature study (Brozovsky et al., 2024) illustrates the temporal evolution of the ten most significant technologies based on the total number of publications. Initially, prefabrication was the most prominent, maintaining this dominance until the late 1970s. In the 1980s, robotics became dominant, con-

tinuing into the next decade. CAD held a significant portion of the literature in the 80s and 90s, but its influence diminished due to the rapid growth of BIM. AI and ML are now considered resurgent technologies in the literature, while VR, AR, MR, and XR have increasingly come to the forefront since the late 1990s, although their relative significance has declined over time. (Brozovsky et al., 2024). The increasing popularity of artificial intelligence and technology is further demonstrated by their growing prominence in various subfields. For instance, a 2023 study (Rangasamy and Yang, 2024) examined articles from 2006 onwards that focused on technology in the field of Prefabricated Construction. The study found that during the initial period from 2006 to 2014, progress was slow, but there was a steep increase from 2015 to 2022, with a similarly strong trend expected for 2023. The strong upward trend is likely due to the widespread adoption of modern technologies such as BIM, AI, and IoT in the PC field, which are prominent topics alongside sustainable construction and modular practices. (Rangasamy and Yang, 2024)

Based on the work of Tsigkari et al., there are basically two main aspects of how AI can be integrated into AEC design processes (Tsigkari et al., 2021; Rafsanjani and Nabizadeh, 2023):

- The first approach includes a surrogate modelling process to replace conventional, time-consuming modelling processes with an economic computational predictive model based on several intelligent simulation results. The surrogate model process can properly detect patterns from historical data in real-time or near real-time, enabling making quick decisions.

- The second approach is considered design-assist modelling which is integrated into the intuition of designers to facilitate architectural processes having no analytical explanations (e.g. optimising the spatial layout of furniture within a space)."

The aim of the research is to collect and categorise AI-based software that enhances the efficiency of building design according to its usage and to examine its applicability in the design process, with a focus on sustainability aspects as well. The research began with a literature review, followed by the identification and examination of numerous AI-utilizing software. After conducting analyses, we determined the phases of the design process in which they can be used. For easier interpretation, this is also presented in a graphical illustration.

# 3. Classification of AI by Application Purpose in Terms of Sustainability

In this section, it would be beneficial to discuss how AI applications, in general, work and how they could potentially benefit the AEC sector. It could be said that AI is a simulation of natural intelligence, a simulation that we are able to process by computer. Such simulations have the capacity to analyse vast quantities of data and to cope with complex sets of overlapping problems. Perhaps its most valuable quality is its capacity for self-learning. Self-learning can be seen to help adaptation in a similar way to parametric design but without any manual intervention. This is because the algorithm rewrites itself repeatedly, based on the input data and the problems to be solved, to provide the best possible solution. (Hey, 2023).

A building's life cycle can be divided into three main phases: design, construction and operation. It is worth noting that these processes are now significantly influenced by the use of artificial intelligence. In this discussion, we will focus on the applications used in the first two main phases, with a special emphasis on energy and optimisation, as these features play an important role in creating environmentally friendly buildings. Below, we categorise and analyse several AI-based software solutions according to their main uses.

## 3.1. Text generation

Large Language Models (LLMs) are generative, meaning they can produce text based on user inputs. LLMs do not fully understand the text but instead recognise patterns from training data and predict which words are likely to follow one another. They are sensitive to input prompts and may provide different responses to differently phrased questions. They do not possess reasoning or critical thinking abilities like humans; their responses are based on observed patterns. In the AEC sector, they are significant for writing various

technical texts, conducting data searches, and summarising proposal materials. Here are a few popular and useful examples from the field (Al-Ami et al., 2024):

- Bing Chat (Microsoft): Bing Chat is a natural language search and response generation tool.
- Gemini (Google):
- WordAi (WordAi Inc.): WordAi is a text rewriting tool that creates SEO-friendly content.
- Quillbot (Quillbot Inc.): Quillbot can summarize long texts in natural language, preserving the main points.
- GPT-4 (OpenAI): The GPT-4 model by OpenAI can generate various types of text.
- Lumar (SEObarátorok): Lumar is a content generator that creates keyword- or topic-optimized content.
- Author (Author AI): Author is an essay generator that creates content in natural language.

Large Language Model (LLM) solutions can assist in gathering sustainability considerations and applying them to plans. They can also help collect and interpret the latest research, as well as generate documentation. Additionally, they can aid in producing technical descriptions and documentation and in promoting and integrating sustainability considerations into project communications, thereby facilitating the spread and adoption of sustainable building practices.

## 3.2. Image generation

Generative image creation AI systems are capable of producing images based on user inputs (prompts). They make predictions and "guess" the elements of the image based on patterns found in their training data. Similar to text generators, they typically require prompts to be controlled, and even an extra space character can result in a completely different outcome. Thus, they do not possess human creativity or artistic sense; the images they create are based on learned patterns. These programs can perform various tasks, including text-driven generation, image-based generation, image expansion, image editing or manipulation (such as background modification), and model-based design in programs like Archicad. (Bundela, 2023)

- Midjourney (Midjourney Inc.): Advanced image generation.
- DALL-E (OpenAI): Advanced image generation.
- DeepArt (DeepArt AG): Applying artistic styles to photographs and visual presentations of designs.
- Runway (Runway ML): Image and video creation tool.
- Adobe Firefly (Adobe): Enables AI-based image creation and editing.

In the field of AEC, these imaging AI systems can be useful for creating visualisation plans, visualising design proposals or creating inspiration for architectural concepts.

From a sustainability perspective, they can provide inspiring visuals in the ideation and initial design phase; for example, a landscape scene can inspire designers. They can also help visualise sustainability work packages, even by creating a working drawing of an engineering system.

## 3.3. Design optimisation, sustainability and simulation

In the AEC sector, these sustainability-focused AI systems can be particularly useful. These tools typically use optimisation functions in addition to AI and typically collect data after loading the model into their own software, 'interpret' it, and then use optimisation and AI to make recommendations for, e.g. changes in building materials, mass modification, etc. (Yezioro et al.,2008) (Xiang et al.,2022)

- Spacemaker (Autodesk): an AI-based urban planning tool that generates alternatives and helps you choose the best solutions.

- Digital Blue Foam: an AI-based urban planning tool that offers green design options.
- Hypar: Cloud-based AI platform for architectural solutions that offers functional and feasible building alternatives.
- Architechtures: Web-based AI building design tool that supports urban planning and architectural decisions.
- Cove.Tool: enables complex energy assessments based on BIM models.
- EnergyPlus: a comprehensive simulation engine that provides better temperature and comfort prediction.

These complex programmes can help, for example, to optimise energy consumption, reduce construction waste and promote green building practices. For example, they can help analyse materials to suggest alternatives that have a lower environmental impact or optimise construction schedules to minimise energy use. In addition, it is very useful for designers to choose a solution that has several modules covering the life cycle of a building and is thus able to analyse the functioning of the building throughout the whole process.

It is important to note that these software are often complex and require extra time to learn. You can't even "see" how it works, so you don't know exactly what it is that has led you to a particular event. browsing through the user manuals can help with this, but it also takes extra time to understand. This may slow down their uptake, but their usefulness is still significant.

### 3.4. BIM

The relevance of BIM has been demonstrated in several pages [references]; the mapping of data to models allows AI technologies to use them. There are already AI-supported functions available in BIM software, and smaller companies are trying to use this data independently to help the building design process with different functions and purposes. These solutions can now be used, for example, to generate visual designs, create model-based documentation, quantify costs, etc. (Bassir et al., 2023)

- Archicad: crowd model-based visualisation/inspiration generation
- Revit: several add-ons are available e.g.: visual designer, model generator from 2D (WiseBIM), text generator for model interpretation (BIMlogiq) etc.
- Aurivus: Scan To BIM. detection and classification of structural elements.
- Sparkel: text-based quantification.
- Swapp: BIM model-based documentation generation.

These solutions can typically help in some of the key areas of design, increasing efficiency, which in itself is a sustainability benefit.

## 4. Analytical Software

Of the applications listed, analytical software and optimisation software deserve a closer look. Digital Blue Foam, Spacemaker and Cove.Tool are applications that have the potential to be the applications of the future in many areas, in addition of course to the very wide range of applications they have today. These applications are described below.

Spacemaker AI is mainly aimed at a narrower market, as already mentioned within urban planning, mainly looking at sun exposure and sunlight in urban areas, and can also be used for urban ventilation simulations. These are, of course, the roots of current urban problems, but if urban ventilation modelling and sunlight analysis could be widely disseminated, future cities could become much more sustainable. The software

also includes a feature that suggests building placement and generates building shapes to aid early decision-making. Autodesk has acquired this software and incorporated it into a comprehensive, multi-functional programme, Autodesk Forma, to support its further development.

Digital Blue Foam (DBF) is a software that has invested considerable resources in its development but is difficult to access in the market and expensive to use. However, the software's artificial intelligence algorithm is surprisingly advanced and is able to communicate live with multiple design programs, back and forth, so that what is optimised by the AI is seen in the design program. This broad interoperability suggests significant potential for interdisciplinary applications that take advantage of the positive features of each software. The software has similarities to Delve, developed by Sidewalk Labs, which is also well suited to urban planning and is developing rapidly in terms of energy analysis of buildings.

Cove.Tool is a cloud-based, web-based software designed to analyse and optimise the energy performance of buildings. In principle, the software supports any CAD program or 3D modelling software that can generate spatial building geometry. It has plug-ins for almost all of these programs that allow geometric data to be easily imported into the analysis software to perform model-based analysis. The only difficulty is that the elements of the designed building that are considered important must be classified in the element properties in the design software using the Cove.Tool add-ons.  Other than that, the software interface (Figure 1) is quite intuitive, as is usual with AI applications, and provides very easy-to-read (graphical, numerical) feedback on all the settings made during the program's workflow.

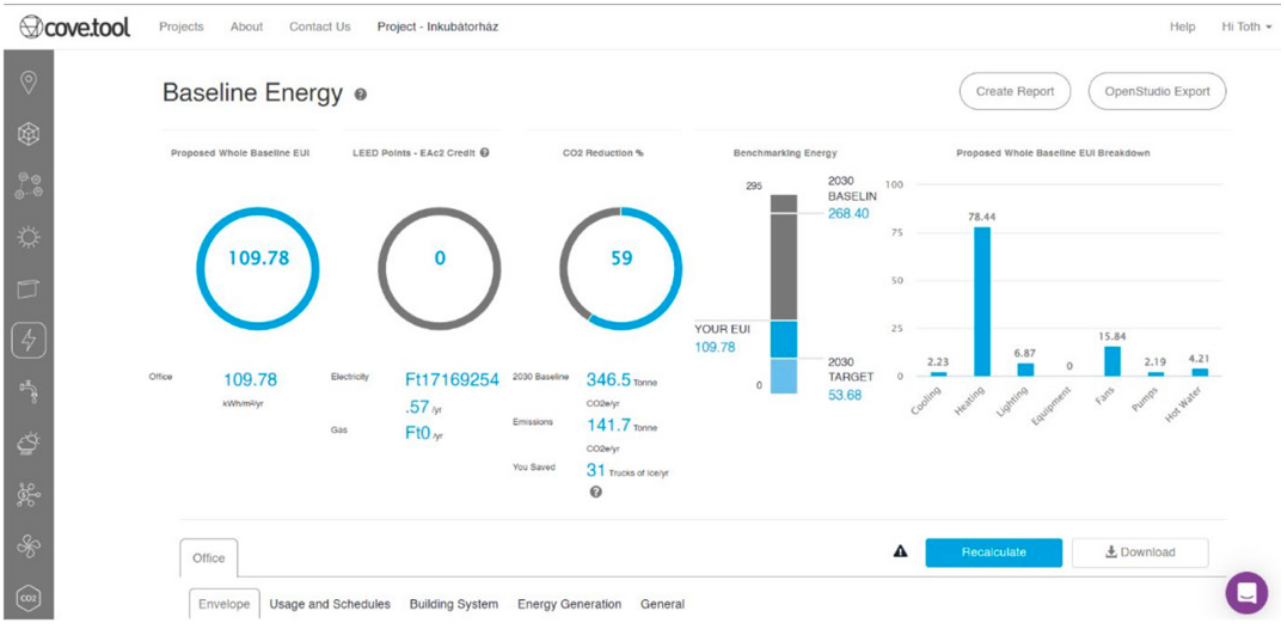


*Figure 1: Cove.Tool energetic analysis interface with diagrams and numerical values*

The software guides you through these workflows (Figure 2), with a sidebar where you can click on the various icons to see what settings you still need to make in order to get a detailed, optimised result at the end of the application. It is important to note that the energy analysis and optimisation in this application are also based on standards. However, the problem is that it does not really support regional or national standards. We can mainly choose from international standards. For example, the IECC (International Energy Conservation Code), but even for national standards, only American standards are included in ASHRAE 2018,2019 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers).

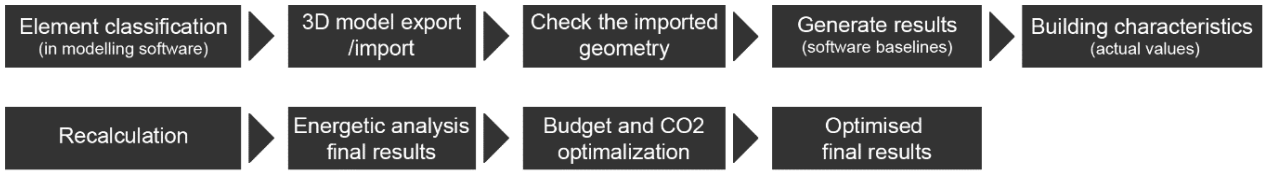


*Figure 2: Cove.Tool Plugin workflow for energy analysis and optimisation*

# 5. Discussion

Artificial intelligence is playing a growing role in the construction industry, and as these tools develop, they will become more and more common in practice. The programmes analysed are characterised by a single objective, and no new full-featured design software has yet been developed. However, there are already solutions such as CoveTool, whose complexity suggests that these tools will be able to do more and more and that the design process and engineering practice will be transformed.

Sustainability is also becoming more vocal, and these new AI-based solutions offer many good solutions to support this. The solutions have been evaluated from a sustainability perspective, and Figure 3 provides several examples of where different software can be applied and the benefits they offer.

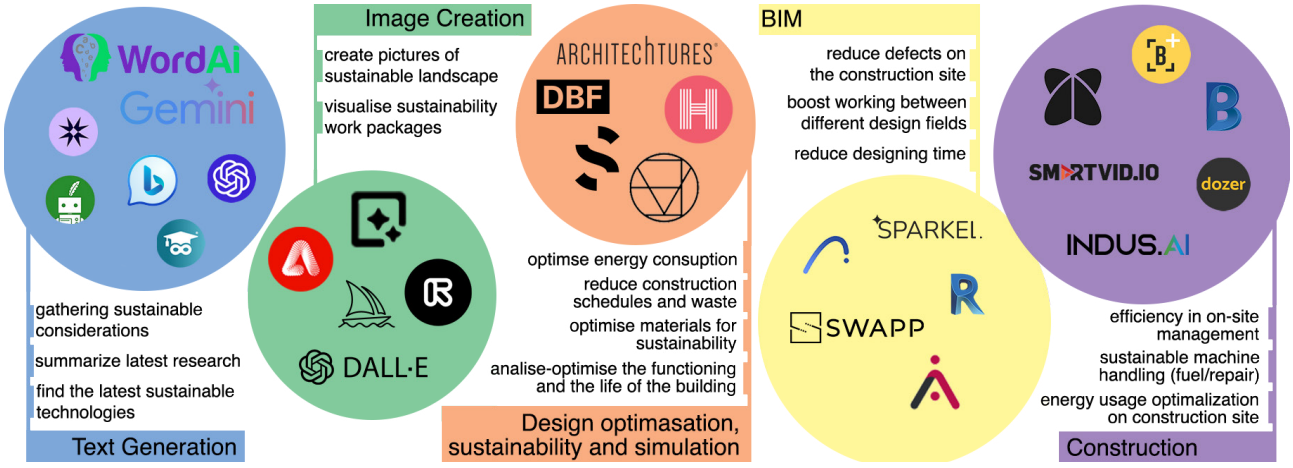


*Figure 3: AI Software tools for the five examined segment of AEC industry with their key roles in sustainability*

Research provides us with tools that can be integrated at different stages of the building process. From design to construction, it is important to consider the use of artificial intelligence, which can help to highlight sustainable aspects. (Debrah et al., 2022) Text generation tools such as WordAI or ChatGPT automate research and provide up-to-date data on sustainability that can be easily integrated into design. Imaging tools are revolutionising the visualisation of sustainability for clients and users. The analysis and simulation of design scenarios, facilitated by DBF, Architectures and Cove.Tool, enables the optimisation of building energy efficiency from multiple perspectives. BIM has already revolutionised teamwork, but AI tools that can be integrated into BIM further enhance collaboration, reduce design errors and shorten design time by identifying problems at an early stage. Artificial intelligence is already being utilised in construction, with Indus.ai and Smartvid.io representing notable examples. During the construction phase, the energy consumption of construction machinery and the amount of construction waste can be optimised. Based on the research, numerous solutions are available that utilise AI technologies to varying extents. Testing and understanding their operation is crucial for conscious use. Therefore, training and education must play a prominent role. This also presents a risk, as the designer may not fully understand why a specific result was produced and, in some cases, might believe a false result due to a minor error in the software. Legal issues raise additional questions for which there is currently no unified regulation.

# 6. Conclusion

The rise of artificial intelligence (AI) affects almost every sector, including the construction industry. AI is rapidly spreading in practice, with more and more software developers creating solutions of various sizes and purposes. Based on a literature review, this article presents the process of AI proliferation and its key characteristics. Additionally, it aims to examine AI solutions thematically by main function groups and provides examples of them. It also addresses their benefits from a sustainability perspective. The solutions are examined in the following categories: text generation, image generation, data analysis and visualisation, design optimisation and simulation, project management and coordination, and Building Information Modeling (BIM). Three analytical software were discussed more deeply as they have a huge future potential. Spacemaker offers urban planning tools focusing on sunlight and ventilation simulations, contributing to more sustainable cities. Autodesk acquired Spacemaker in 2020. Digital Blue Foam offers not only energy analysis but also cost analysis and spatial analysis. Cove.Tool provides robust energy analysis and optimisation, though it primarily supports international standards, limiting its adaptability to regional needs.

The listed examples do not cover nearly all available products, but they clearly demonstrate that solutions exist to significantly aid processes at every stage of a building's lifecycle. These solutions can assist with documentation, preliminary research, energy consumption optimisation, construction waste reduction, more efficient planning, and more. They not only enable more efficient and accurate planning but also offer dedicated solutions for energy assessments, version comparisons, and rapid calculations during the concept phase, allowing for an early examination of sustainability issues. Regardless of building scale, these solutions can contribute to more efficient planning, though they are particularly beneficial for larger or more complex projects. This is because managing and considering a large amount of data can be challenging for humans, whereas AI does not have such limitations.

Artificial intelligence is continuously evolving and will provide increasingly complex solutions in the field of design. Education is very important so that more and more designers understand what these solutions can be used for, how to use them, and approximately how they work, enabling them to apply these tools consciously.

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# NEW WAYS IN RACE SPORTS – BE THE 21ST DRIVER

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**Motorsport has long been a very popular and explorative environment within the automotive industry. Recently, simulated racing has gained significant popularity. The rapid evolution of artificial intelligence (AI) technology has led to the development of agents with superhuman capabilities, capturing attention across various domains. SimRacing provides an ideal platform for comparing these agents.**

**This paper presents a system capable of generating a digital twin of real-time racing events within a simulated virtual environment. By doing so, it enables simulator drivers and AI algorithms to compete against real racing professionals with minimal risk of crashes. We outline the essential system requirements and propose key specifications. Additionally, the paper details the primary sub-functions and system architecture for this purpose.**

## 1. Introduction

Motorsport has always played a crucial role in automotive innovation and development. Car racing is not only a test of speed and technological performance but also serves as an experimental laboratory where new solutions can emerge. In recent years, simulated racing, or SimRacing, has garnered increasing attention from both racers and technology developers. This virtual platform offers racing enthusiasts the opportunity to test their skills in a realistic environment while eliminating the risks associated with real racing.

Furthermore, simulated racing represents not only a cost-effective alternative to real-world testing, but eliminates the need for physical resources such as fuel, tires, and vehicle parts, which are typically consumed in the real-world motorsports. By conducting races virtually, there is a significant reduction in carbon emissions, resource usage and waste generation. These factors directly contribute to the industry's sustainability efforts. Simulators, on the other hand, offer a controlled environment where drivers can practice, test new strategies, and refine their skills without incurring the high costs associated with physical testing. This financial efficiency makes SimRacing an attractive option for both amateur and professional racers seeking to optimize their preparation and performance.

The rapid development of artificial intelligence (AI) technologies has opened new horizons in simulated racing. AI-driven agents capable of superhuman performance are attracting growing interest from researchers and developers. These agents have demonstrated their effectiveness and innovative potential on the racetrack. SimRacing provides an ideal platform for testing and comparing the capabilities of these AI agents, enabling direct competition between real racers and AI with minimal risk.

This study presents a system capable of generating a digital twin of real-time racing events within a simulated virtual environment called the Driver 21 project, where you can be the 21st driver among 20 real-world racing drivers. The concept of a digital twin allows simulator drivers and AI algorithms to compete with real racing professionals without the risk of accidents. Furthermore, the system has been designed to accommodate multiple future use cases, ensuring that it not only meets current demands but also adapts flexibly to future developments and expansions. In the following sections, we detail the essential system requirements, propose key specifications, and describe the primary sub-functions and system architecture necessary for creating and operating the digital twin.

# 2. System descriptions

## 2.1. Digital twin of racing cars

A digital twin of a racing car is a highly detailed, virtual replica of the physical car, which includes its mechanical components, dynamics, and environmental interactions. This digital counterpart is created using a combination of data from the real car, advanced simulation technologies, and real-time data analytics. The digital twin is designed to mirror the behavior and performance of the actual car as closely as possible, providing a comprehensive representation of its characteristics and capabilities.

The utilization purpose of the digital twin will determine its level of detail and components. The digital twin continuously receives data from various sensors on the actual racing car, including telemetry data, engine parameters, tire pressure, suspension dynamics, and more. This data is used to update the virtual model in real-time, ensuring that it accurately reflects the current state of the physical car and providing a high-fidelity simulation environment.

Engineers and drivers can use the digital twin to run simulations of different racing scenarios, weather conditions, and track configurations, exploring a wide range of potential situations without the need for physical testing. The digital twin can predict how the car will perform under various conditions, helping teams to optimize setup and strategy for enhanced performance on the racetrack. By analyzing the digital twin, teams can identify potential issues or areas for improvement without risking damage to the actual car, facilitating iterative design and development processes.

Drivers can utilize the digital twin to practice and refine their driving techniques and strategies in a virtual environment that closely mimics real-world conditions. It allows for safe experimentation with different driving lines, braking points, and overtaking maneuvers, enabling drivers to hone their skills and improve their performance without the risks associated with on-track testing. Overall, the digital twin of a racing car serves as a valuable tool for engineers, drivers, and teams, offering insights, optimization opportunities, and performance enhancements in the highly competitive world of motorsport.

## 2.2. System analysis

The project requirements were influenced by several input factors. Before starting to create the requirements, a comprehensive analysis of the application areas was made. This analysis included the mapping of different functions and the assessment of their importance in different areas. This approach enabled us to make the parameters both comparable and scalable.

For a thorough evaluation, six different use cases were examined in detail. Each use case was analyzed based on seven different criteria. These criteria were then rated on a scale of 0 to 5, providing a clear and quantifiable measure of their importance in each context (see scoring system in ***Table 2***). This granular approach allowed us to get a nuanced view of how different features affect different aspects of the project.

The use cases besides Driver 21 included:

- TV broadcast, aimed at improving the viewing experience and engagement for audiences
- Race control support, which enhances the efficiency and accuracy of race management
- Track safety, dedicated to ensuring the safety of the racing environment for all participants
- A.I. self-driving development support, which aids in the advancement of autonomous driving technologies
- Race engineer support, which provides tools and insights to optimize race strategies and car performance.

*Table 2: Scoring system description*

| | Real time / latency | Camera quantity | Camera resolution | Camera FPS | Position accuracy | System complexity | Bandwidth |
|---|---|---|---|---|---|---|---|
| 0 | Offline | N/A | N/A | N/A | N/A | N/A | N/A |
| 1 | >10s | 1 | <HD | 30 | <20m | 1 data bus | <5Mbps |
| 2 | <10s | 2 | - | - | <5m | 2 data buses | <30Mbps |
| 3 | <3s | 4 | HD | 60 | <2m | 4 data buses | <50Mbps |
| 4 | <1s | 6 | - | - | <50cm | 6 data buses | <100Mbps |
| 5 | <100ms | >6 | 4k | 120 | <10cm | 10 data buses | >100Mbps |

The results of the analysis are visually represented in the form of a radar diagram as shown in Figure 1. This diagram effectively illustrates the relative weight of each criterion among different functions. The radar diagram serves as a valuable tool for comparing the importance of individual criteria in different scenarios, highlighting which aspects are the most critical in each use case.

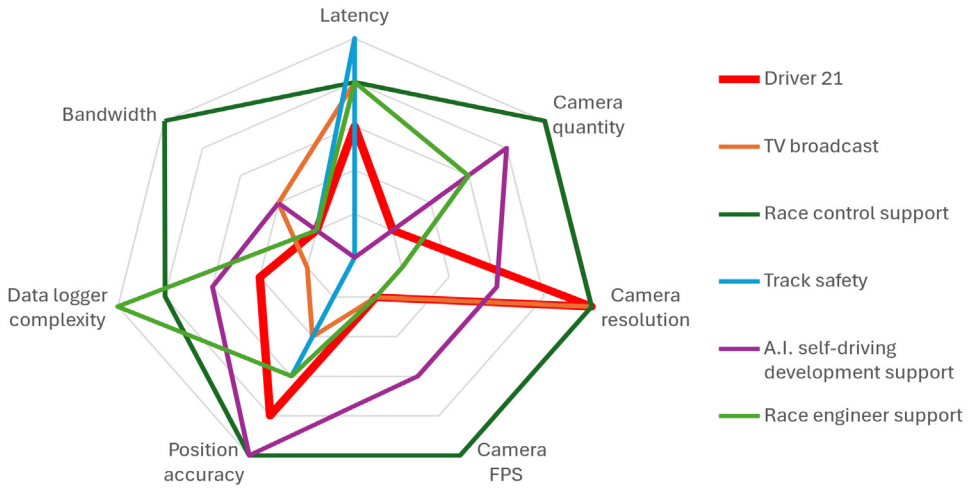


*Figure 1: Radar diagram of the use case analysis*

By displaying the data in this manner, the strengths and weaknesses of each feature relative to the seven criteria become evident. This not only facilitates the prioritization of requirements but also ensures that the most important aspects receive adequate attention. Consequently, this comprehensive analysis and its visual representation provided a solid foundation for project requirements, facilitating informed decision-making and strategic planning. From the radar chart, the necessary baseline requirements can be derived, ensuring that the Driver 21 use case is satisfied 100 %. By comparing these baseline requirements with our available resources, the requirements were assembled accordingly. To ensure that all necessary aspects are covered and to prioritize effectively, the radar chart was scrutinized to identify the core criteria that must be met for the Driver 21 use case. This detailed analysis provided a clear picture of the essential functionalities and their relative importance. By cross-referencing these fundamental requirements with our resource capabilities, strategic planning and resource allocation were conducted to meet the demands of the Driver 21 use case. This approach not only ensures that the key requirements are addressed but also allows for efficient utilization of resources. Thus, the radar chart has been instrumental in highlighting the critical requirements, enabling us to prioritize and structure the project requirements effectively. This structured approach ensures that project goals are met while optimizing resource utilization.

The primary goal of Driver 21 is accurate positioning, which has driven most of the requirements to ensure the highest precision in this area. To achieve this, several concepts were thoroughly examined and mapped out. Following this, comprehensive market research was conducted to determine available options and components that can be utilized off the shelf to achieve our objectives.

During this process, various scenarios were explored and evaluated for their potential. After excluding less viable options, detailed decision matrices were created to aid in selecting the most optimal solution.

These decision matrices enabled systematic comparison of alternatives based on key criteria such as accuracy, cost, and ease of integration. This ensured the selection of the optimal solution to achieve precise positioning in Driver 21.

# 3. System overview

The primary functions of the system are as follows:

- Measurement of the racing car's exact position, dynamics, and other technical parameters.
- Transmission of these data to the cloud.
- Storage, processing, and manipulation of the data in the cloud using algorithms tailored to specific use cases. This supports the creation of digital twins for the cars' positions and dynamics.
- Integration of the race simulator with the processed data to visualize the digital twins of the racing cars in the virtual space, enabling virtual races between simulator pilots, gamers, and the digital twins of real cars.

To achieve the above functionalities, four distinct functional units need to be developed:

- Onboard-System (OBS)
- Race track Infrastructure
- Cloud Infrastructure
- Simulator

## 3.1. Onboard-System (OBS)

The onboard-system is a critical component installed in every racing car participating in the virtual race. Its primary function is to transmit necessary data for creating digital twins of the racing cars, including precise position on the track, orientation, dynamic properties, and other technical parameters in real-time via a mobile network. This unit does not process data locally; it focuses on synchronized data transmission, allowing for a more compact and lighter system that integrates easily into racing cars.

The system collects data from various sensors on the car, such as GNSS for position tracking, accelerometers, and gyroscopes for measuring dynamics, and telemetry systems for monitoring engine performance and other technical parameters. Real-time data collection and transmission are crucial for maintaining the accuracy and reliability of the digital twin.

The onboard-system contains the following components: Dual GNSS receiver, IMU (Inertial Measurement Unit), Cameras, Main unit.

The main unit manages various peripherals, including cameras, GNSS receivers, and IMUs. It collects data from the racing car's CAN (Controller Area Network) system via CAN interfaces, ensuring comprehensive data acquisition. The main unit is responsible for time-synchronized data collection from all sensors and peripherals, transmitting the data in real-time to a remote cloud-based storage system via a built-in 5G module.

## OBS partitioning

The main goal of the Driver 21 project is to ensure accurate and reliable positioning. During the project, several concepts and partitioning options were examined from a systems perspective. These options were analyzed in the context of comprehensive market research. Initially, various concepts were developed and then partitioned differently at the system level. Throughout the project, six different scenarios were developed where identical numbers corresponded to the same product. For example, in scenario C, as depicted in Table 1, the system comprises three distinct units: a camera unit, an inertial navigation system (INS) that integrates GNSS and an IMU with a compass, and a logger equipped with a 5G broadcast module. The purpose of this was to map which approach provides the best accuracy and reliability. Each option was analyzed in detail to understand its functionality and integration possibilities. The subsequent step involved market research to identify existing solutions corresponding to the developed options. Our objective was to select technologies that best aligned with the requirements of Driver 21 and required minimal development time and cost for integration. Throughout the evaluation process, options that were unavailable (B) in the specified partitioning or economically unfeasible (E and F) were excluded.

*Table 2: System partitioning table*

| Functional elements | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| Camera | 1 | 1 | 1 | 1 | 1 | 1 |
| GNSS | 2 | 2 | 2 | 2 | 2 | 2 |
| IMU + compass | 2 | 2 | 2 | 3 | 2 | 3 |
| Logger + pipeline + sync | 2 | 2 | 3 | 4 | 3 | 4 |
| 5G module | 2 | 3 | 3 | 4 | 4 | 5 |

A decision matrix was developed from the remaining options to facilitate the selection of the optimal alternative. This matrix ranked the options based on objective criteria such as cost-effectiveness, integrability, development resources, competence, compatibility with existing technologies, and others, using a weighted scoring system. By aligning with the defined requirements of the Driver 21 project and leveraging data from market research, the most suitable solution was identified.

The evaluation led to the determination that the optimal solution for partitioning the positional sensor involves using separate GNSS and IMU units, as indicated in Table 1 under Option C. A comprehensive analysis of various concepts and market options ensured that the selected solution would be optimal both technically and economically, facilitating the successful implementation of the project.

By prioritizing positioning accuracy and leveraging market-available solutions, a robust set of requirements was developed to efficiently meet the objectives of Driver 21. This approach not only ensures adherence to the highest standards of precision but also optimizes resource utilization. The meticulous analysis and strategic planning inherent in this process have established a solid foundation for the project's successful implementation, addressing critical aspects and achieving primary goals effectively.

## 3.2. Race track infrastructure

The track infrastructure consists of two subunits:

RTK System: Supports precise positioning through Real-Time Kinematic setup, enhancing GNSS accuracy by providing real-time corrections. This ensures a much higher level of precision than a stand-alone GNSS receiver.

5G Network: Establishes a 5G mobile network along the track for full coverage, enabling real-time transmission of data from OBS to the cloud. High bandwidth and low latency are essential for handling large data volumes promptly and reliably.

Installation involves careful planning and calibration of hardware like RTK stations and optimization of the 5G network for consistent coverage.

### 3.3. Cloud Infrastructure

The cloud infrastructure is where data processing occurs. Key functions include:

- Time-synchronized storage of data recorded during the race for each racing car in a database. These data provide the basics for designing other use cases.
- Data convert process to ensure the predefined interface between database and simulator program
- Determining the localization and orientation of racing cars using sensor fusion algorithms and combining vehicle models. This functionality poses one of the greatest challenges in this project, as sensors like GNSS receivers, even with modern RTK systems, fall far short of the advertised centimeter-level accuracy in racing car speeds. High-precision GNSS receivers update positions at a frequency of 10-50 Hz, depending on the type. This implies that a racing car travelling at 300 km/h can cover a distance of approximately 1.5 to 8 meters between two position updates, introducing significant uncertainty into localization determination.

### 3.4. Simulator

Many high-quality racing simulators are available on the market, allowing virtual racing against virtual opponents or multiple live simulator drivers. These simulators are widely accessible and popular. The goal is to establish a cooperative relationship with an existing simulator company to integrate the digital twins of the racing cars into their platform.

The integration involves developing an interface that allows the simulator to access and use the real-time data from the digital twins. This interface must ensure that the virtual environment accurately reflects the conditions of the real-world race, providing a realistic and immersive experience for the virtual pilots. The integration process includes rigorous testing and validation to ensure that the performance and behavior of the digital twins in the simulator match those of the actual racing cars.

## 4. Racing car localization problem

As it has been mentioned earlier, the pose of the real car has to be estimated as accurately as possible to create its appropriate digital twin. The location estimation task can be performed with a wide range of sensors (Table 1), but everyone has some disadvantages: The GNSS measures the position directly, but significant noise and delay could occur (Falco et al., 2017), the IMU is biased, and the errors are double-integrated to calculate the position (Thrun et al., 2006), cameras can be utilized only in areas with full of well recognizable features, and often prior teaching is necessary (Bloesch et al., 2015), and the wheel encoder-based estimation (wheel odometry) that suffers from parameter uncertainty (Fazekas et al., 2021). Since the main focus is on the location of the vehicle, the core sensor is the GNSS, but it should be completed to reach the required estimation performance, i.e. 100 Hz frequency, delay-free timing, and centimeter-level accuracy.

A widely used method is the GNSS & IMU INS fusion. Due to the high-performance requirements, compensation for the biases of the IMU and the delay of the GNSS should be integrated into the fusion. In most of the algorithms, the mathematical method is the Kalman-filter, which assumes Gaussian noises. The nonlinearity can be handled with its two enhancements, the Extended and Unscented Kalman-filter (Gustafsson and G. Hendeby, 2012). Furthermore, suppose the accuracy is limited because of the unmodelled dynamic of the noises. In that case, the particle filter is the appropriate choice, with which the non-Gaussian errors, e.g. in the bias model of the IMU, can be captured.

When the focus is on the requirement to be as accurate as possible, the architecture of the state estimation filter has a high impact. In the loosely-coupled connection, the processed signals, e.g. GNSS position, orientation and velocities, are fused with the dynamic signals. However, in this way, there is no loopback to

the raw signals process layer from the filtered ones that can limit the performance. Another way is the tightly-coupled architecture, where the raw pseudoranges and Doppler measurements are integrated into the estimation. It is clear that the lowest error of the final pose estimation can be reached in this formulation, but the algorithm will be more complex and difficult to manage in several contexts.

Furthermore, the accuracy can be increased by considering signals from the CAN network. However, these can not be accounted for directly, only as inputs of various vehicle models: wheel rotation and torque in the tire model for the longitudinal, steering encoder in the bicycle model for lateral, and suspension potentiometers in the roll/pitch model for vertical dynamics. Since the vehicle models are based on many parameters, a calibration algorithm is necessary also to properly include the information of these signals. This expansion of the filtering method generates more difficulty in the tightly coupled architecture, e.g. in the tuning process of the estimator. Nevertheless, in the era of machine learning when the computation effort and data demand are less matter, new AI-based ideas could be developed (Fazekas and Gáspár, 2024).

# 5. Conclusions

The development and implementation of a digital twin system within the Driver 21 project represents a significant advancement in the field of motorsport and simulated racing. This system offers a comprehensive and highly detailed virtual representation of real racing cars, providing valuable insights and optimization opportunities for engineers, drivers, and teams. By utilizing real-time data analytics, advanced simulation technologies, and AI-driven agents, the digital twin system bridges the gap between virtual and real-world racing environments. The primary goal of achieving precise positioning and reliable data transmission has driven the project's requirements and system architecture. Through careful market research, detailed analysis of different concepts, and strategic planning, the project has identified the most suitable technologies and components to meet these demands. The integration of a dual GNSS receiver, IMU, cameras, and a robust cloud infrastructure ensures accurate and real-time data synchronization, essential for creating high-fidelity digital twins. The Driver 21 project exemplifies the potential of digital twin technology in revolutionizing motorsport. It offers a versatile and scalable solution that not only meets current requirements but is also adaptable to future developments. The project's success underscores the importance of precision, innovation, and strategic planning in advancing the boundaries of simulated racing and automotive engineering. In addition to its technical achievements, the Driver 21 project also contributes to the sustainability goals of the automotive and motorsport industries. By shifting a significant portion of racing development and testing into the virtual realm, the system reduces the need for physical testing, lowering the consumption of resources such as fuel, tires, and vehicle parts. This virtual approach minimizes the environmental impact of traditional motorsport activities, promoting a more sustainable and eco-conscious future for the industry.

# Nomenclature

- AI – Artificial intelligence
- CAN – Controller Area Network
- GNSS – Global Navigation Satellite System
- IMU – Inertial Measurement Unit
- INS – Inertial Navigation System
- OBS – Onboard-System
- RTK – Real-Time Kinematic

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# AUTONOMOUS RACING COMPETITIONS: A REVIEW OF PLATFORMS, SOFTWARE DEVELOPMENT, AND SUSTAINABILITY CONTRIBUTIONS

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**Motor racing challenges the limits of speed, performance, and control. However, human drivers face physical and mental constraints that autonomous vehicles can overcome using advanced sensors, algorithms, and computing power. This paper reviews the current state of autonomous racing, focusing on key events, platforms, and series such as F1Tenth, the Indy Autonomous Challenge (IAC), and the Abu Dhabi Autonomous Racing League (A2RL). The aim is to assess the development and deployment of autonomous software systems, examining technical challenges related to perception, planning, control, learning, and safety. Additionally, we analyse the scalability of these solutions from simulation to real-world environments and evaluate their contributions to sustainability, including promoting STEM education, advancing vehicle safety, and fostering public acceptance of autonomous technologies. Through this review, we highlight how autonomous racing contributes to both the motorsport community and broader society by accelerating research and innovation.**

## 1. Introduction

The idea of autonomous driving technology has captured the imagination of engineers and researchers since the 1930s and has since become increasingly important in the automotive industry. It is considered of great importance for the future of transportation because of the social significance of its wide-ranging benefits. These include making transportation safer by reducing accidents caused by human error. In addition, autonomous vehicles can use technologies such as Vehicle-to-Everything (V2X) and adaptive algorithms to increase the efficiency of vehicles. Examples include increasing fuel efficiency or even reducing traffic congestion by using intelligent routing and coordinated driving technologies. These technologies also have the potential to make on-demand car sharing and future taxi services more efficient, leading to fewer cars on the road and, consequently, lower emissions. Classical motorsport has long contributed to automotive innovation and, indirectly, to sustainability by providing the financial and engineering platform for expensive research. These innovations have made today's vehicles more efficient and safer. Similarly, autonomous racing is gaining importance, as it can help overcome barriers to self-driving cars by creating an environment that facilitates research results that might otherwise be delayed or impossible. Existing reviews mainly focus on the implementations of autonomous software systems. For example, Betz et al. (2023 analyse software used in the Indy Autonomous Challenge (IAC), while Sauerbeck et al. (2023) explore perception systems for autonomous racing. These works focus heavily on software and hardware development; however, they often overlook aspects such as testing, deployment, and scalability in real-world environments. This article fills these gaps by addressing not only software systems but also the testing, deployment, and scaling methods used in autonomous racing platforms. Although not covered exhaustively, these topics provide a broader context for understanding the challenges and contributions of autonomous racing. Insights gained from direct participation in the F1Tenth, and Abu Dhabi Autonomous Racing League (A2RL) competitions are incorporated to provide a unique perspective on the practical challenges and contributions of these

platforms. The main focus of the presented article is addressing these gaps by describing the novel testing, deployment and scaling methods, along with sustainability considerations and their positive impacts.

# 2. Discussion

## 2.1. Autonomous motor race series

In recent years, more and more autonomous competitions have emerged and become important. These series have been created with different objectives and focus on a wide range of areas to challenge the competing teams. The format of the competitions, the vehicle platform used, and the choice of venue and regularity vary according to the objectives and the financial implications of the events (Betz et al., 2022). The following analyses the three most impactful race series, including the vehicle platforms and race event formats.

### F1Tenth (F1/10)

The vehicle platform used by the competition is a reduced 1:10 scale Radio-Controlled (RC) car utilising an electrical engine. The sensor set mounted on this base is simple and standardised. The sensors that can be used for environmental perception include planar Light Detection and Ranging (LiDAR) and Red-Green-Blue-Depth (RGBD) cameras. In addition, an Inertial Measurement Unit (IMU) sensor is in the combined steering and engine control unit to measure the dynamic properties of the car. There may be component variations to the proposed reference layout, subject to approval by the organisers. There is also a proposed layout for the vehicle body, computer, and sensors (O'Kelly et al., 2019). Competition rounds are held at prestigious conferences worldwide. To participate, teams must pass a static check for rule compliance and a dynamic check for object avoidance. Qualifying begins with time trials, scored on the fastest lap and most consistent laps without a crash. Based on the qualifying, head-to-head rounds are held, where two cars compete to complete the race distance in the shortest time.

### Indy Autonomous Challenge (IAC)

The vehicle platform is based on the Indy Light series design and is complemented by the incorporation of sensors, actuators and computing units enabling autonomous applications. The sensor configuration prioritises research flexibility over cost, with multiple mono cameras, radars, and 3D LiDAR sensors to provide redundant and robust 360° perception. In addition to these, it has various chassis, IMU and redundant Global Navigation Satellite Systems (GNSS) sensors for vehicle localisation, powered by a 2.0-litre turbocharged engine and a 6-speed sequential semi-automatic gearbox (Betz et al., 2023). The competition requirements are designed to vary from race event to race event to encourage teams to push innovations in the utilised technology. From static object avoidance to overtaking manoeuvres, oval tracks and full track layouts, the participating teams have to solve various challenges. These focus on different areas of autonomous technologies to drive the development of algorithms in a focused way.

### Abu Dhabi Autonomous Racing League (A2RL)

The vehicle platform is based on the 2023 Super Formula cars modified with a self-driving kit for autonomous racing. It features multiple mono cameras, 3D LiDAR sensors, radars for 360° perception, a combined IMU-GNSS sensor, and various chassis sensors, including engine speed and tyre temperature sensors, among others. The car uses the same internal combustion engine and semi-automatic gearbox as in the IAC for the vehicle's powertrain. A high-performance computer in the cockpit connects to sensors via various interfaces, such as an automotive switch, for a reliable ethernet connection. One of the key elements of the competition format is that it wants to focus more on multi-car events, which is reflected in the overall prize allocation. The main event is a 4-car full race situation with attack and defence challenges in 2-car pairs as a prerequisite. Teams must demonstrate overtaking manoeuvres and the corresponding defensive behaviour to try to prevent them. The teams also participate in time trials, which are still the most successful events to date. These details are based on firsthand experience, as there is currently limited literature documenting the technical specifications of the vehicle platform and competition format used in A2RL, with our recent work providing a more detailed description of this topic (Demeter et al., 2024a).

## 2.2. Developing autonomous software

There are several approaches to autonomous systems, the two most important of which are the classical pipeline approach and the learning-based pipeline approach, shown in Figure 1. In the former, a threefold perception-planning-control decomposition of the problem can be observed while the latter shows an end-to-end learning based black box type structure. In the following, the high-level concepts listed here are presented with the addition of safety, which encompasses all software modules in both approaches.

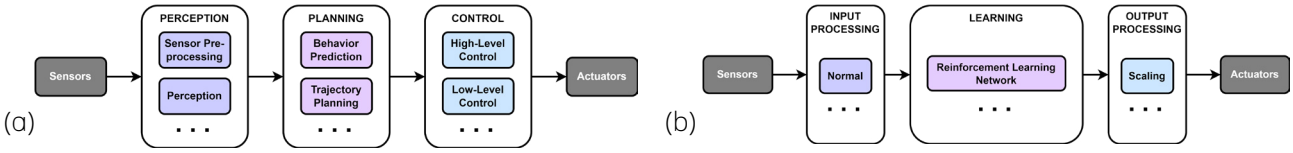


*Figure 1: Examples of pipelines: (a) A classical pipeline and (b) A learning-based pipeline.*

### Perception

Perception is a crucial function of autonomous driving and a great development challenge. The software must process data from various sensors to create a model of the surrounding environment that can be interpreted by the planning algorithm. While racetracks are simpler than general motorways or urban roads, their boundaries are often hard to perceive due to long distances between walls and a lack of classifiable landmarks. High-speed environments further complicate the task, requiring algorithms to perform with minimal latency and runtime. Most research in this field focuses on the localisation problem since online mapping is not strictly necessary for a predefined racetrack. TUM Motorsport used vision-based object detection for opponent recognition in IAC (Sauerbeck et al., 2023). The latest research also demonstrates a novel side slip estimator by integrating Lidar Odometry with the Pacejka tyre model, validated on the AV-21 platform (Toschi et al., 2024). In competitions where the track is unknown, localisation without some kind of mapping or object detection is not sufficient. To address this, camera-LiDAR sensor fusion-based landmark detection approaches can be used with Simultaneous Localisation and Mapping (SLAM) algorithms (Alvarez et al., 2022).

### Planning

The planning algorithm interprets the environment model from perception and plans a feasible path or trajectory that accounts for the vehicle's dynamics. Path planning algorithm typically consists of a global and local planner: the global planner focuses on a high-level, optimal trajectory around the whole racetrack, whereas the local planner plans a trajectory based on the current immediate surroundings to navigate between obstacles or to overtake an opponent (Trumpp et al., 2024). In current trends, the most relevant research combines both technologies to achieve optimal performance (Raji et al., 2022). In addition, the planner module has several other functions that are not directly related to trajectory planning. These may include following, stopping, overtaking and velocity profile fitting (Stahl et al., 2019). Another important function of the planner is mission planning, which can be used to implement various predefined actions or to adapt to the current competitive task.

### Control

The control algorithm serves as the executor of the decisions formulated by the planning algorithm. It is a crucial part of the overall autonomous system, ensuring that the vehicle's movements are smooth, safe, and precise. This area is divided into two parts: lateral and longitudinal control. The former is tasked with handling the vehicle's steering and side-to-side movements, while the latter regulates the vehicle's forward and backward movements, which include handling acceleration and deceleration. There are two main control approaches used in autonomous racing: geometric and predictive approaches. Geometric controllers track a reference path using only the geometry of vehicle kinematics and the reference path. In the Pure Pursuit method (Coulter, 1992), the vehicle's steering angle is adjusted to minimise the distance to a target

point on the desired path to ensure that the vehicle follows the planned trajectory accurately. It operates by continuously selecting a look-ahead point on the path and steering the vehicle towards it. The Stanley controller (Hoffmann et al., 2007), another commonly used approach, minimises both the lateral distance and heading error. This has the advantage that a lot of domain-specific knowledge can be added (Fazekas et al., 2024). The state-of-the-art solutions are usually based on predictive controllers like Model Predictive Control (MPC). Learning-based MPC solutions can identify and tune the vehicle model online and improve lap-by-lap (Kabzan et al., 2020). The Tube-MPC concept promises cautionary performance in case of nonlinear effects or disturbances at the limits of handling while being capable of operating at the level of an MPC (Wischnewski et al., 2022).

### Learning

Learning-based solutions can cover a broad range of applications in the pipeline. There are algorithms that are designed to solve only a specific kind of task (Srinivasan et al., 2020) and some that model the entire self-driving system in a black box layout. For example, the former can be used to manage and plan multi-vehicle situations, while the latter is used to provide direct control signals from unprocessed sensing data. There is great potential in end-to-end learning-based solutions. In many other relevant fields, superhuman performance has been achieved using this approach. The realisation and feasibility of these largely depend on the observation with which the model is constructed. It is also important whether the solutions in question are model-based or model-free (Hell et al., 2024). The former is limited in its capabilities by the accuracy of the constructed model, while the latter can achieve performance that exceeds current modelling capabilities.

### Safety

In autonomous racing, while no human driver is at risk, vehicle safety is critical to prevent crashes and dangerous situations. In lower-speed competitions, cars are equipped with a remote emergency system for shutting down the vehicle if needed. However, in high-speed competitions like IAC and A2RL, where speeds exceed 200 km/h, software plays a key role in mitigating risks. While the cars are still connected via 5G for remote control, the software is responsible for performing critical sanity checks to prevent failures and ensure safe operation.

## 2.3. Deploying and testing autonomous software

Deploying the algorithms under development is a complex task that requires many problems to be addressed. Depending on the domain, the initial phase of algorithm development is usually done by replaying recorded data. The next phase involves running a series of simulation tests to ensure that the software is capable of handling a variety of situations and outlier cases. The final step is to test the developed algorithm on a real vehicle and iterate the development cycle based on the data and experience collected.

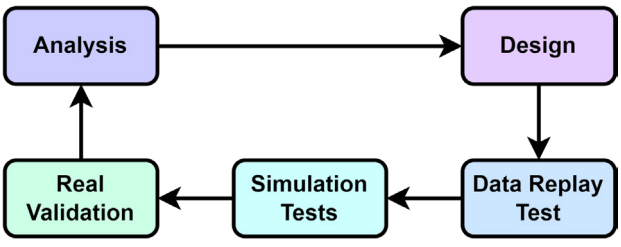


*Figure 2: The development lifecycle of autonomous software*

The following are two important aspects of the development process that can cause difficulties leading to deployment.

## Sim-to-Real gap

The sim-to-real gap refers to the difference between the performance of an AI system in a simulated environment and its performance in the real world. This gap arises due to the inherent complexities and unpredictability in the real world that are not captured by simulation. Real-world conditions are often simplified for computational efficiency, leading to inaccuracies in the used models, such as vehicle or environmental models. This problem is relevant for control systems, learning-based solutions, and the field of perception. A system that is perfect in simulation will behave differently in reality or even fail to work completely. This raises various safety considerations when validating autonomous systems. Eliminating the differences in the physical models is practically impossible due to high computational needs. However, refining the models and incorporating unexpected events captured on real data into the simulation can iteratively reduce the unobserved part of the environment (Manivasagam et al., 2023). Improving the validation process of a module influenced by the sim-to-real gap using statistical analysis and modelling is also a highly desirable and relevant approach among control systems (Daza et al., 2023).

## Scaling up architecture and algorithms

One of the biggest challenges in testing autonomous racing software is conducting the initial experiments. Testing a simulation-validated algorithm in a sim-to-real gap-constrained environment can lead to unexpected behaviours. This is also complicated by inherent bugs typical of software development, which can also cause undefined events. These can all cause crashes, which can have serious financial consequences. To mitigate this, firstly, the algorithms can be tested on small-scale, low-cost platforms, such as the F1/10 presented above and gradually upscaled. As a result, the initial tests, which may have the most uncertain outcomes, can be performed at a lower cost. This allows for learning about potential errors and understanding the impact of the sim-to-reality gap with lower consequences. The tested algorithms can then be used on platforms with progressively increasing scale and cost. However, the process of scaling up an algorithm is far from trivial and involves many challenges. To enable this, it is first necessary to have a hardware-software architecture that makes this possible (Demeter et al., 2024b). It is important to use an architecture that is suitable for use on a variety of vehicle platforms of different configurations and scales. This provides an opportunity to test algorithms in a common environment using different sensors and hardware devices. It is also necessary to design the algorithm itself with scalability in mind. This is not always achievable; for example, due to varying perception sensor sets, this can be particularly difficult.

## 2.4.Sustainability contributions

Autonomous vehicles and this new form of motor racing have many useful contributions to sustainability. In addition to representing and promoting a form of transportation that would increase efficiency, autonomous racing has many positive social benefits. The following are several important aspects that characterise this.

## Promotion of STEM Education

Autonomous racing series showcases the practical application of Science, Technology, Engineering and Mathematics (STEM) concepts in an exciting and engaging manner. This can inspire students and young people to pursue careers in these fields. The three most relevant competition series currently presented above also place significant emphasis on this area. For example, the F1Tenth competitions also directly support the education of STEM students by providing the necessary course materials and laboratory exercises to prepare for the competition. Students and academic institutions are also actively being involved in these competitions and research. The A2RL series also believes it is important to stimulate students' interest in this field of engineering. Huge events are organised around the competitions, with various additional tournaments to encourage younger participants. There is also a possibility of entering RC self-driving car races like F1Tenth or even races with simulators used by the participating teams.

## Development of Safer Autonomous Vehicles

Commercial self-driving cars are undergoing extensive testing in the automotive industry, but testing at the limit of handling and at extreme speeds is not an option in an industry largely focused on cost minimisation.

This is where self-driving competitions can be of great help, as they create an opportunity for the time and financial resources to be available for these experiments. This allows researchers to explore uncharted territory for autonomous vehicles that will help make the technology safer. These competitions play a major role not only in supporting these test cases but also in promoting research with expensive technologies and sensors. In many cases, the vehicle platforms used have very expensive hardware, to which research centres' access would, in many cases, be limited without this opportunity. Thanks to this, a significant amount of state-of-the-art research findings are produced because of these competitions.

### Public acceptance

People need to trust autonomous vehicles and feel confident in their safety, but challenges remain, including the lack of a mature regulatory system, which remains an open discussion. Despite statistics showing that these vehicles cause fewer accidents than human drivers, negative news coverage often overshadows their reliability. Autonomous racing can help improve public perception by demonstrating the technology's safety and performance at high speeds. As these competitions attract large audiences, they provide a valuable platform for building trust and encouraging public acceptance.

## 3. Conclusions

In conclusion, autonomous racing platforms like F1Tenth, IAC, and A2RL are not only advancing the capabilities of self-driving technologies but also contributing significantly to safety improvements, software scalability, and sustainability. For instance, A2RL has demonstrated the feasibility of autonomous multi-car racing at speeds exceeding 200 km/h, which tests the limits of autonomous vehicles in terms of handling. Additionally, these platforms are essential for reducing the "sim-to-real" gap, as their real-world application provides data that simulation environments cannot fully capture. These competitions play a crucial role in promoting STEM education and enhancing public trust in autonomous vehicles, which is vital for broader societal acceptance. The scalability and testing methods discussed here are paving the way for more robust and adaptable autonomous systems. Future research should continue to explore the integration of learning-based systems with classical control methods, and further investigation into the sustainability impacts of these platforms is needed to quantify their long-term benefits. This review highlights the ongoing and future significance of autonomous racing for both the automotive industry and society as a whole.

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# MILD HYBRID DRIVETRAIN DEVELOPMENT FOR MOTORSPORT APPLICATION

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Mild hybrid systems represent a promising avenue for enhancing the efficiency and performance of conventional vehicles. Yet, their application in motorsport faces significant challenges due to the stringent demands for power, durability, and reliability. This paper details the development of a mild hybrid drivetrain for Touring Car Racing (TCR) vehicles centred around a crankshaft starter generator. It encompasses the design, simulation, and testing processes of the system, highlighting both the advantages and obstacles associated with integrating mild hybrid technology into high-performance racing vehicles. Test results from the prototype demonstrate noticeable improvements in lap times, providing valuable insights into the system's real-world performance under rigorous track conditions. Through an in-depth analysis of how the drivetrain impacts lap times, this study identifies specific enhancements to vehicle competitiveness enabled by mild hybrid technology. Moreover, lessons learned during the development process inform future iterations, suggesting critical optimisations such as weight reduction and improved power transmission systems. The findings underscore the potential for mild hybrid systems to contribute to sustainable motorsport while offering directions for future research and development aimed at creating high-performance, cost-effective solutions that align with contemporary environmental aspirations.

## 1. Introduction

This project aimed to design, test, and implement a drivetrain supplement for Touring Car Racing (TCR) vehicles that aligns with 21st-century environmental goals. The objective was to create a standardised conversion package for all teams. While motorsports prioritise speed and performance, these often come at the cost of increased environmental impact, challenging sustainable development principles.

Motorsport has historically driven automotive innovation, with racing technologies often transitioning to public road vehicles (Tran et al., 2020). However, growing environmental concerns demand solutions that balance performance with sustainability. Mild hybrid systems address this by using small electric motors to assist internal combustion engines, improving efficiency, reducing emissions, and enhancing performance through added torque and energy recovery. Integrating mild hybrid technology into motorsports improves lap times while showcasing innovations aligned with future road vehicle trends. This project demonstrates how such systems enhance track performance and promote sustainable practices in the automotive industry.

### 1.1. Hybrid systems in the automotive sector

Mild hybrid systems have emerged as a significant innovation in the automotive sector, offering a bridge between conventional internal combustion engines and full hybrid or electric vehicles. These systems, which typically employ a small electric motor to assist the engine during acceleration and recapture energy during braking, provide several key advantages. Firstly, they improve fuel efficiency by reducing the load on the engine, leading to lower fuel consumption and emissions. This is particularly beneficial in urban driving conditions, where stop-start traffic is common (Autoweek, 2024). A mild hybrid vehicle uses a small electric motor to assist the internal combustion engine, enhancing fuel efficiency and reducing emissions without enabling

fully electric driving. These systems typically feature a 48 V battery and support functions like regenerative braking (Liu et al., 2019).

Secondly, mild hybrid systems enhance vehicle performance. The electric motor can provide additional torque, improving acceleration and overall drivability. (Bao et al., 2017). This is especially useful in larger vehicles, where the extra power can help to overcome the weight disadvantage. Furthermore, the energy recovery during breaking can be used to power electrical systems in the vehicle, reducing the load on the alternator and further improving efficiency (SEG Automotive, 2024).

Finally, the adoption of mild hybrid technology is a major step towards the electrification of the automotive industry. It allows manufacturers to gain experience with electric powertrains and battery management systems, while consumers can become accustomed to the characteristics of electric drive. Moreover, it provides a cost-effective solution for reducing $CO_2$ emissions, helping manufacturers meet increasingly stringent environmental regulations. Thus, mild hybrid systems play a crucial role in the ongoing evolution of the automotive sector (Schaub et al., 2021).

### 1.2. Alternative drivetrains in Motorsport

The integration of electric hybrid drivetrains into motorsports represents a significant evolution in the field, merging the exhilaration of racing with the necessity for environmental sustainability. These drivetrains, which combine the capabilities of an internal combustion engine with one or more electric motors, are revolutionising motorsports. They offer a unique blend of performance and efficiency, providing instant torque for improved acceleration, recovering energy during braking for increased efficiency, and indirectly, through improvements transferred from motorsport to public roads, reducing emissions for a smaller environmental footprint (Schöggl et al., 2011).

Integrating these drivetrains into motorsport vehicles presents a complex yet rewarding challenge. It requires careful optimization of power flow among the internal combustion engine, electric motors, and energy storage systems to reduce energy consumption and emissions while maintaining vehicle performance and reliability. This integration goes beyond simply adding an energy storage system and a means of converting stored energy into mechanical forces. It also involves regenerating mechanical energy back into renewable power, creating a more sustainable powertrain system (Zhu et al., 2018).

Furthermore, the utilisation of electric hybrid drivetrains in motorsports extends beyond performance, it also establishes a precedent for the future trajectory of the automotive industry. As the industry aggressively seeks fuel efficiency enhancements through the hybridization of production vehicles, motorsports are adopting analogous architectures to maintain relevance with current passenger car trends. This trend is anticipated to persist as the industry transitions towards more sustainable practices (Al-Adsani and Beik, 2022).

In this paper, the development steps will be represented, such as Design and Simulation, Manufacturing and Testing and the main results will be discussed, such as lap time comparisons with and without the system. The conclusions and potential future development areas regarding the Mild Hybrid Kit are also discussed.

## 2. Development process

Motorsport itself is barely sustainable, but if all the aspects are being considered using lifetime analysis, it can be clearly stated that motorsport gave the public some real, truly remarkable innovations as well (IEA, 2024). During the development process, it was intended that the system and product must somehow promote the future of sustainable motorsport racing. During project planning, it became obvious that every tenth of a second gained on the racetrack could lead to saved grammes of carbon dioxide on public roads, since if the system ensures better lap times, it can be transformed into fuel savings on the public roads, assuming similar speed profiles.

The development process begins with a feasibility study to ensure that the return on investment is achievable within two to three years. One of the primary goals has always been to create a hybrid kit that complies with the Fédération Internationale de l'Automobile (FIA) regulations, specifically FIA Appendix J Article 253

(FIA, 2024). Compliance with FIA standards is essential for increasing public awareness of motorsport. After an extensive benchmarking period, the project team recognised that providing excellent value for money is crucial in customer racing. Teams often operate with limited resources and do not have the enormous support of original vehicle manufacturers. It turned out that there are some possible competitors, like the British Touring Car Championship (BTCC), where the engineering solution is quite complicated but, more importantly, extremely expensive (Mitchell, 2022).

As a consequence of the reasons above, it had become mandatory to keep the system simple, ensure easy mountability to the original FIA homologised racecars, and to design something which is considerably cheap to manufacture. By the end of the conception design period, the team ended up with a detailed requirement and specification list, and the main aspects and functions were pre-described of the Mild Hybrid Kit. The team also circumscribed the important and mandatory sub-units of the system.

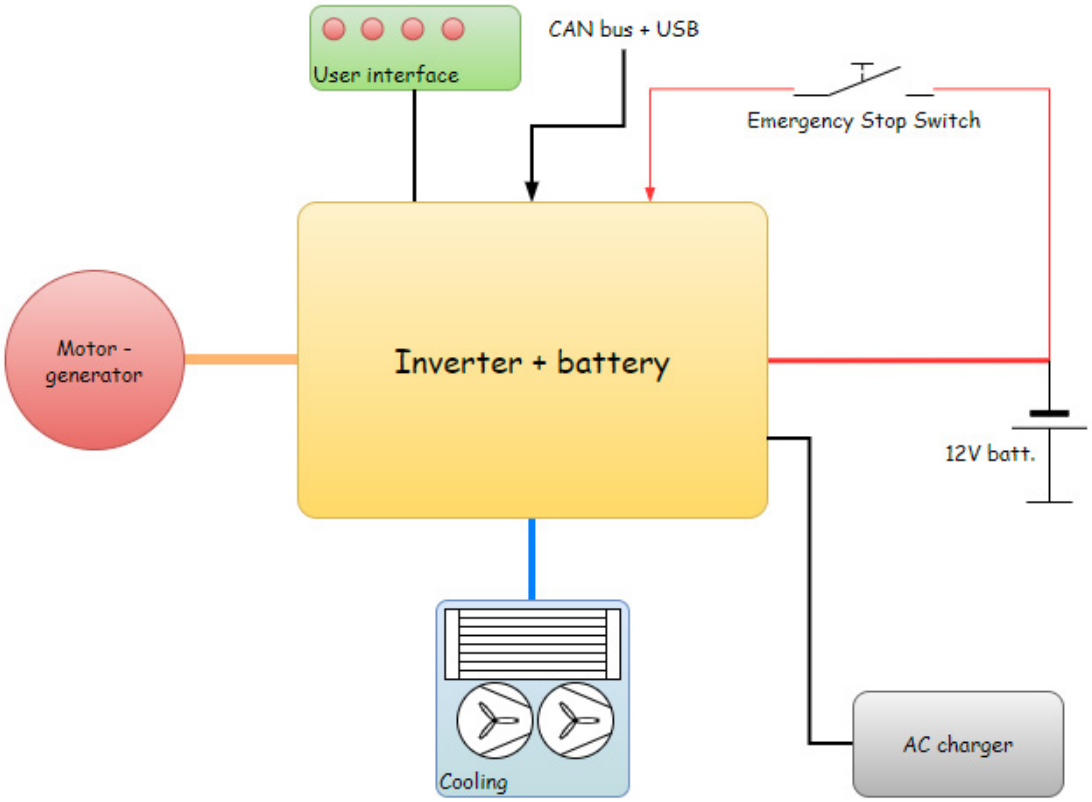


*Figure 1: The main components of the Mild Hybrid Kit, and the integration of the sub-units to the original racecar design and simulation*

## 2.1. Desing and simulation

With the installation of the Mild Hybrid Kit, competing teams are required to replace the original alternator (generator unit) with a motor generator unit (MGU). The main unit of the kit, the Energy Unit, is mounted beside the driver's seat, where the driver can control the entire system. Due to the typically high temperatures at most racing venues, teams are also given the option to install a cooler at the rear of the racecar. In addition to these subsystems, the team developed a human-machine interface (HMI) that allows the driver to monitor and manage the system's state of charge (SoC) in real time. The team determined that one hour would be the required timeslot for installing the system into the racecars. Minimal maintenance was a priority in the design period, as the target customers, racing teams, generally focused on fine-tuning the car itself. The Key performance indicators were the maximum added weight, the peak power of the system, and the maximum system runtime per lap (Beisheim and Stotz, 2013).

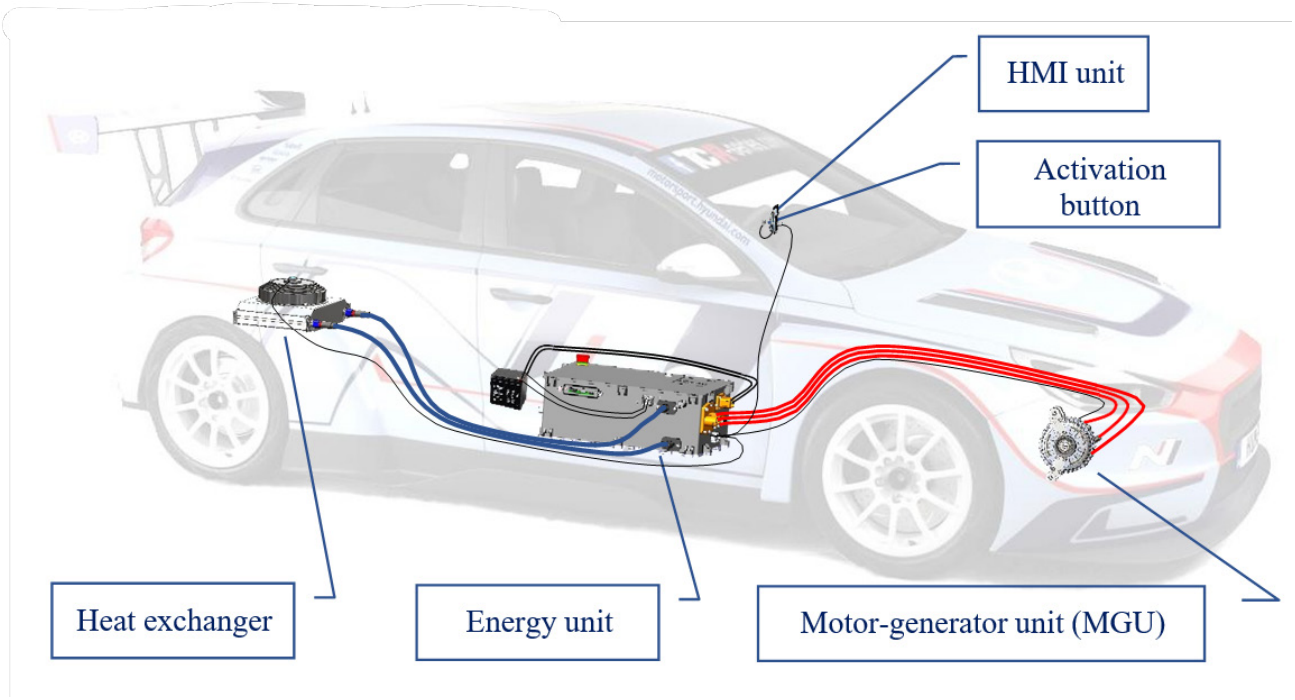


*Figure 2: Mounting of the subsystems in an FIA homologized TCR racecar*

Based on the feasibility study and mechanical analysis of the car's V-belt, boundary conditions were established for the system's realistic performance capabilities. These include the maximum shaft power measured on the alternator shaft, the torque derived from the car's speed, and the operating ratio, which indicates how many seconds per lap the driver can utilize the additional power from the system. Lap time simulations were conducted using OptimumG's OptimumLap software (OptimumG, 2024). The input conditions for the simulation included a total mass of 1280 kg and a loaded power of 15 kW, with using sensitivity analysis, the optimal system usage durations per specific sections of a given lap were determined. The figure below illustrates the threshold where the power increases, assuming 15 kW performance, equalising the system's added mass, assuming a limit of 6 seconds usage time per lap at the Hungaroring circuit (Salazar et al., 2018). Throughout the design process, the goal was to exceed these initial parameters as much as possible. Final data, including track performance and specific heating metrics, will be discussed in the "Testing" chapter.

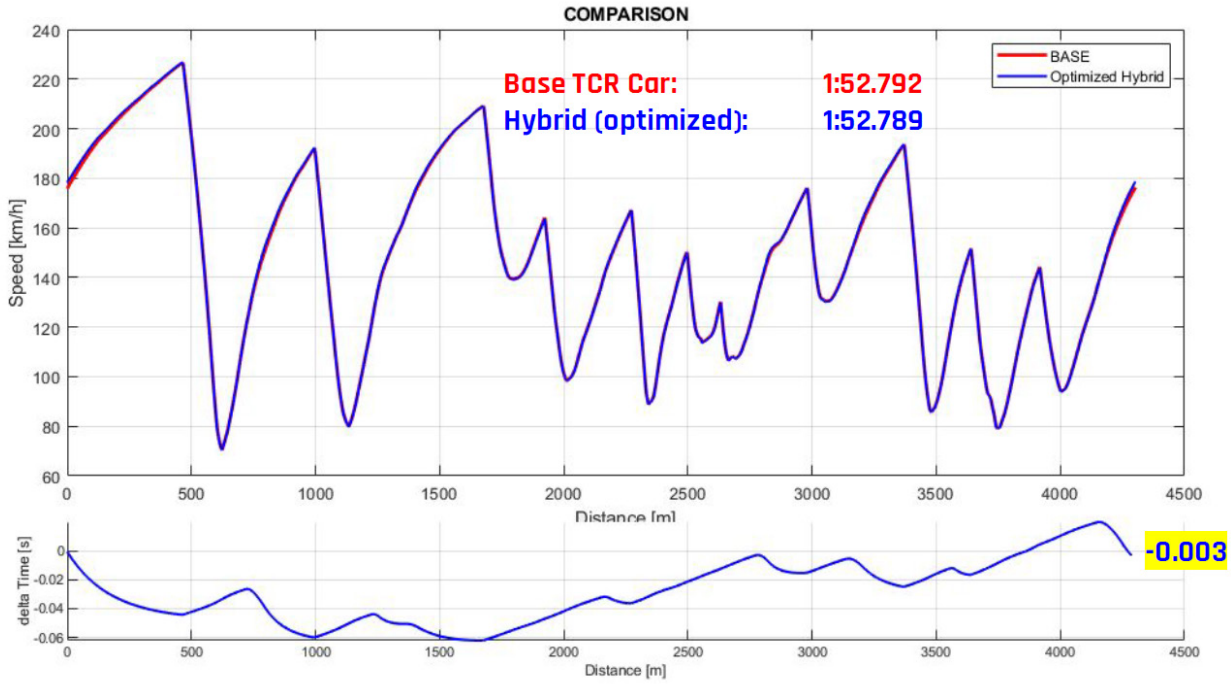


*Figure 3: Plot of speed versus elapsed time on a full lap at the Hungaroring*

Following the simulations, new targets were established for electrical and mechanical design. These included a target power output of 17 kW, with additional power delivery planned for 10 to 15 s every 100 s.

## 2.2. Manufacturing and Testing

The next phase of development involved producing prototypes. This phase covered a range of manufacturing techniques, from basic Computer Numerical Control (CNC) machining to the more intricate process of spot-welding battery cells. The manufacturing process then progressed with the assembly and testing of sub-assemblies. Special attention was given to testing each battery cell, with all measurements meticulously recorded, as the use of lithium polymer cells carries inherent risks (Rao et al., 2023).

## 2.3. Integration

Once the manufactured and commercially available parts were received, assembly and sub-assembly processes commenced. A specialised test team was hired to professionally install the prototype into the vehicle and conduct tests according to predefined measurement protocols. The first testing series was carried out at a closed airport, the ZalaZone automotive proving ground, and the Brno racetrack. The final test involved a live, measured lap at Brno, where assumptions and design decisions were validated with real lap-time data.

# 3. Results

As mentioned in the introduction, the most important characteristic of a racing car is the speed it can deliver on the track. The tests have been conducted on a track which is familiar to the European TCR teams, and the lap times achieved during tests are comparable with other, preexisting results. The selected testing team provided a driver with a proven track record in international series so that performance differences due to driver performance could be minimised (TCR Eastern Europe, 2023).

## 3.1. Lap time and test results

According to the simulated results, optimal lap performance is achieved when the Mild Hybrid system is deployed proportionally on all straights based on their length (Ebbesen et al., 2018). For instance, if a circuit has two straights—one 1000 meters long and the other 500 meters—the ideal use of the system follows a 2:1 ratio (Frederick and Dixon, 2020). It is also crucial to note that the possible benefit from the system depends heavily on the driver's skills, as there are conditions where activating the system may be unnecessary. For example, when the driven wheels are at the limit of traction during acceleration, using the system could lead to wheel slip rather than added performance.

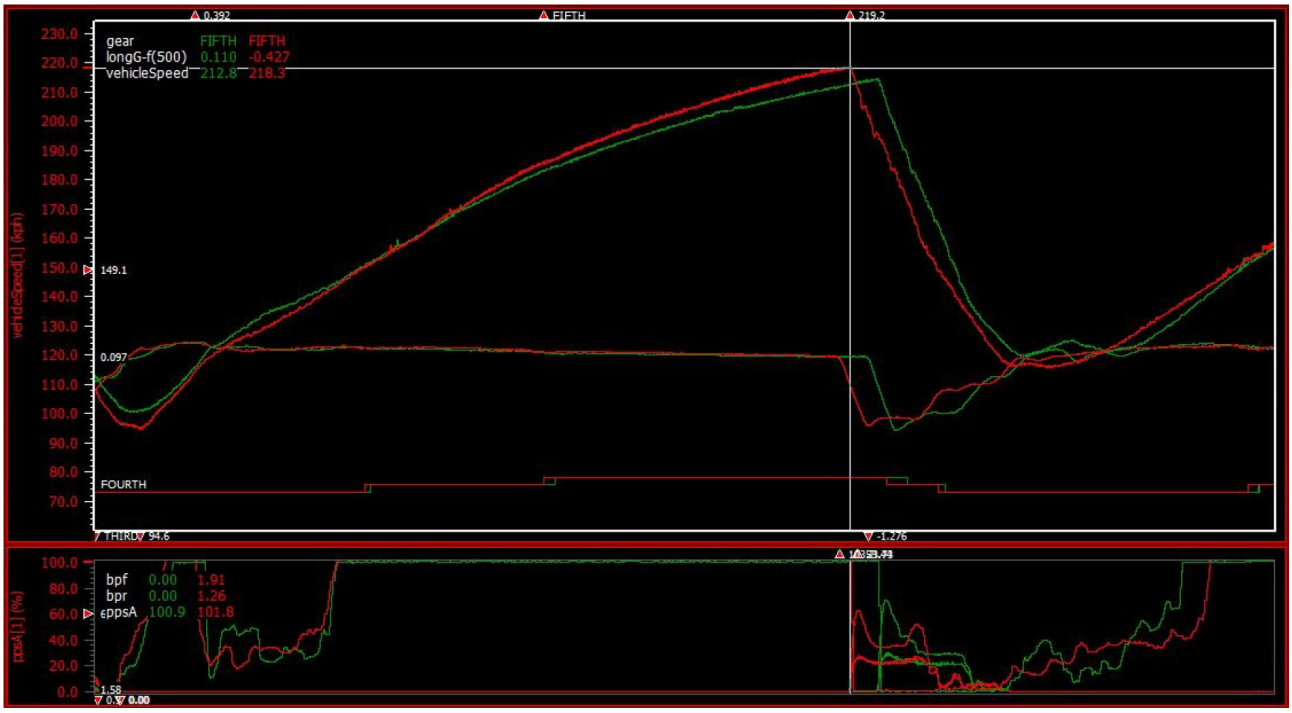


*Figure 4: Speed differences at the Brno finish line for a homologous TCR car with and without the Mild Hybrid system (red line with the system, green line without the system)*

There are many different measures of race car performance, focus on two in particular: the total time it takes to complete a lap and the top speed on the straights. It is easy to see why these two factors are key to success. The former is a fundamental determinant of competitiveness, as it can be used not only to radically improve the starting position but also to improve the lap times in the endurance events. The latter, on the other hand, can be a key factor when defending against other riders and during overtaking situations. The measured data yielded the following results at Brno racetrack:

Lap time achieved without using the system: 2:12.452.

Lap time achieved using the system: 2:13.056.

Maximum speed at the finish line without the system: 212.8 km/h.

Maximum speed at the finish line with the system: 218.3 km/h.

A particularly key factor, however, is the feedback from the drivers immediately after getting out of the car, who also commented positively on the car's behaviour when using the system.

### 3.2. Lessons learned

In the final stages of design, production, and testing, key insights emerged for future iterations. One primary issue was the battery pack's size and weight (Khanna et al., 2022). While the prototype added only 21 kg—significantly less than the 70 kg system used in the BTCC—there is potential to reduce weight by 1.5 kg without compromising capacity. Additionally, the transmission between the motor generator and the engine crankshaft proved limiting, as the V-belt slipped at around 17 kW power output. Future iterations could enhance performance by using a ribbed belt, allowing the system to reach its full 22 kW potential.

## 4. Conclusions

The research and development project of the Mild Hybrid Kit has demonstrated significant promise in improving both the lap times and overall performance of Touring Car Racing (TCR) vehicles. Through rigorous testing, the system provided a tangible competitive advantage, with notable gains in straight-line speed and improved lap times. Despite adding only 21 kg to the vehicle's total mass, the system showed a clear advantage, especially in defending positions and overtaking manoeuvres during races. The field tests at the Brno circuit validated the initial design assumptions, with the hybrid system improving top speed while keeping lap times competitive.

Key lessons from the project highlight the importance of refining the transmission system and battery pack. The current V-belt-driven connection to the crankshaft presented limitations at higher power outputs, suggesting that a ribbed belt or alternative transmission system could enable greater power delivery and improve performance. Additionally, a reduction in battery pack weight is feasible without sacrificing system performance, which would further optimize the car's balance and handling on the track.

For future iterations, the focus should be on enhancing the system's power-to-weight ratio, improving the energy management system, and exploring more efficient cooling solutions. Additionally, expanding testing to a wider variety of circuits and conditions will provide deeper insights into the system's adaptability. These developments will ensure that the Mild Hybrid Kit continues to offer a cost-effective, high-performance solution for racing teams while contributing to sustainable practices in motorsport.

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# ESTIMATION OF GROUNDWATER RECHARGE IN THE SZIGETKÖZ ISLAND AREA USING HYDRUS UNSATURATED MODELING

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The Szigetköz region in northwest Hungary remains ecologically fragile. It lies in the middle of the Danube River and is part of a network of rivers in the region. In the past 40 y, the groundwater and surface water levels have fluctuated over a wide range due to anthropogenic influences. This paper discusses recent efforts to predict the contribution of surface infiltration water to the shallow groundwater table throughout the island and focuses on groundwater movement within the area. The approach is to apply Hydrus unsaturated flow software at different scales using 1, 2, and 3-dimensional models. The models will require meteorological, groundwater, and soil moisture data to assess and predict the impacts of irrigation, local water conservation practices, stormwater collection, and pumping for drinking water. While this study presents preliminary analyses to demonstrate proof of concept, anticipated scenarios include effects of climate change, river and control channel level changes, and land use practices. The advantage of this approach is its versatility in examining many different scenarios and evaluating their impact at local (~100-500 m) meso (500-1500 m) and large (2000 m+) scales.

The research advances our knowledge of hydrological processes in the Szigetköz Island area, underscores the importance of sustainable groundwater management practices, and provides insights into optimizing water resource allocation while ensuring the long-term sustainability of groundwater reserves. It highlights the significance of groundwater recharge and discharge zones in sustaining ecosystem services and maintaining hydrological balance.

## 1. Introduction

The Szigetköz Region has been a focal point for study by scientists, engineers, agronomists, and regulatory and economic development agencies. The "inland delta" of Szigetköz supports a unique floodplain ecosystem that provides a habitat for numerous fish, birds, and mollusk species. Its area is 375 km$^2$, and its elevation is 115–125 m above sea level in the northwest (Upper- Szigetköz) and 110–115 m in the southeast (Lower- Szigetköz). Geologically, the Szigetköz area is a part of the Little Hungarian Plain (Kisalfold), which developed during the Middle Miocene subsidence and the filling up of the alpine orogeny between the Eastern Alps and the Western Carpathians. The sediment carried by the Danube continuously fills the sinking basin of the Kisalfold. The Pliocene (Pannonian) sandy-clayey sediment sequence is more than 2,000 m thick at the deepest point, while the Quaternary sand/pelite and gravel layers comprise the Szigetköz's top 100–500 m. The Upper Pannonian's sand, silt, and clay deposits are composed of fine-grained sediments with low hydraulic conductivity that underlies the gravel surface layer and exhibit high hydraulic conductivity. A Holocene overburden layer covers the surface of the alluvial fan and measures 0–6 m thick, with a conductivity typical for fine sand.

### 1.1. Pre and Post HPP groundwater conditions

Alterations to the complex system of channels began in the 19$^{th}$ century to improve navigation and provide flood protection, as shown in Figure 1. Hydropower construction in the mid-late 20$^{th}$ century diverted about

80 % of the average flow from the main channel and significantly impacted the adjacent floodplain system (Kovács et al., 2015).

The area's subsurface aquifer connects closely to the surface water network, which also resulted in a significant decline in the level of shallow groundwater aquifer. The Upper Szigetköz floodplain replenishment systems were constructed in 1995, relying on gravitational flow without pumping. The situation has since improved through diverting water back to the old riverbed and constructing a submerged weir. From 2014 to 2015, the system expanded to the Lower Szigetköz, including ecological restoration of the Mosoni-Danube. Fish passes provided a means for migration. The Mosoni-Danube outlet structure, completed between 2019 and 2022, now maintains higher channel levels along its lower reach. The Danube formerly recharged the shallow groundwater, but today, the main riverbed taps the shallow groundwater aquifer. Critical hydraulic structures operate in Slovakia and Hungary, emphasising water bodies and connectivity. Upstream controls, particularly at Rajka, play a crucial role. Discharge agreements between Hungary and Slovakia determine water allocation between the Old Danube and floodplain systems, regulated by the Dunakiliti barrage and submerged weir.

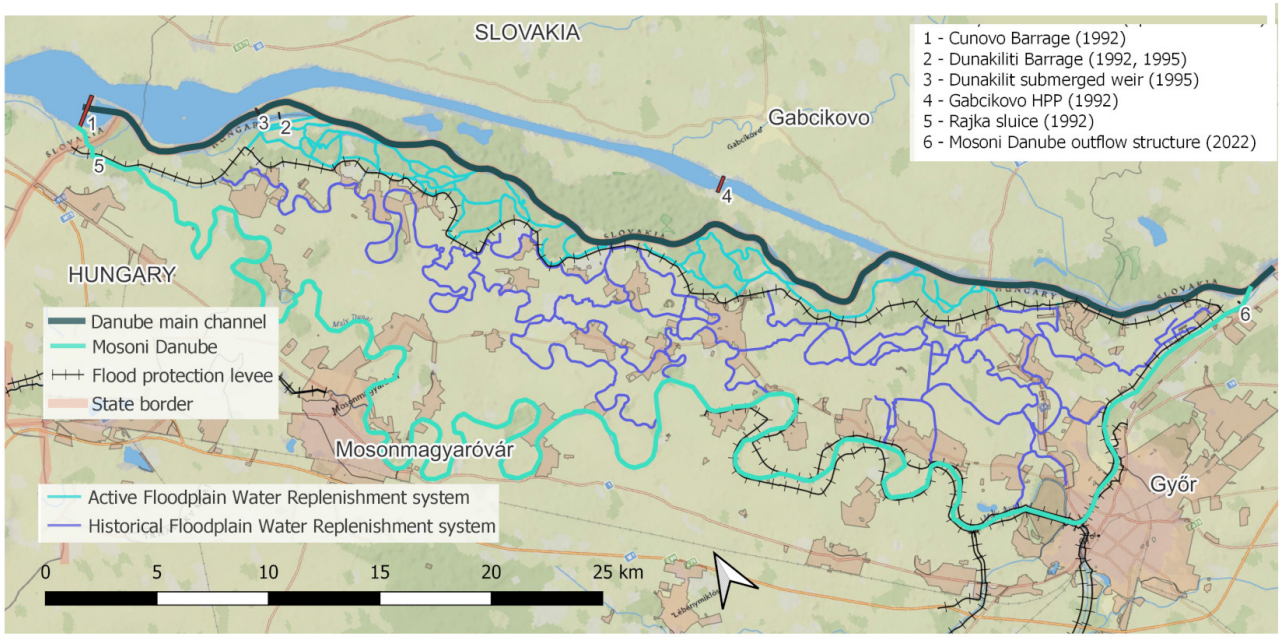



*Figure 1: Szigetköz region showing active and historical canal systems and main control structures*

## 1.2. Impacts of measures on the environment

Implementing water replenishment systems following the diversion of the Danube has brought about significant positive changes in the affected region. Surface and groundwater levels are higher than pre-diversion conditions, with surface water levels in the active floodplain meeting levels from the 1950s. The restoration of diverse aquatic habitats has been successful, as evidenced by surface and groundwater levels in the Szigetköz floodplains. A joint Hungarian-Slovak monitoring system began in 1995, with results summarized in annual reports. The water replenishment restored the biodiversity of the Szigetköz river branch system. Many fish species returned to Szigetköz after continuous rehabilitation activities from 1993 to 2022. Forest growth in the Szigetköz floodplain has been monitored since 1986, with the diversion of the Danube in 1992 leaving a lasting impact. Artificial floods and major flood events have influenced forest growth positively, emphasising the interplay between water dynamics and ecosystem health.

In agriculture, particularly in central Szigetköz, permanent lowering of groundwater levels due to the Danube diversion initially led to a decline in crop yields. However, water replenishment efforts have helped restore yields close to previous levels. Restoring active and historic floodplain branches has also fostered ecotourism in the region (Kálmán and Bene, 2023). The late 1990s and early 2000s witnessed an increase in camp-

ing sites and canoe rentals, with further development occurring after the spatial extension of replenishment systems in 2014-2015. This increased activity and improved environment have caused an increased effort to understand groundwater movement throughout the region. The implications of better understanding the movement of water, nutrients, potential contaminants, and other chemical and biological components are compelling.

## 1.3. Groundwater Movement and Monitoring

The main factor affecting the hydrogeological conditions in Szigetköz is that the Danube runs through the highest section of its alluvial fan in a region known as the "hanging valley." Water that filters through its gravel bed percolates in an SSE direction until it reaches the Hanság canal belt and the Rábca River along the Moson-Danube line. The Danube's northern by-channel, which extends into Csallóköz, Slovakia, simultaneously represents the baseline of water entering the NE bank. Overall, the hydrogeological conditions in Szigetköz are highly dynamic and complex and influenced by various natural and human factors. Understanding these conditions is critical for effectively managing and conserving the wetland ecosystem.

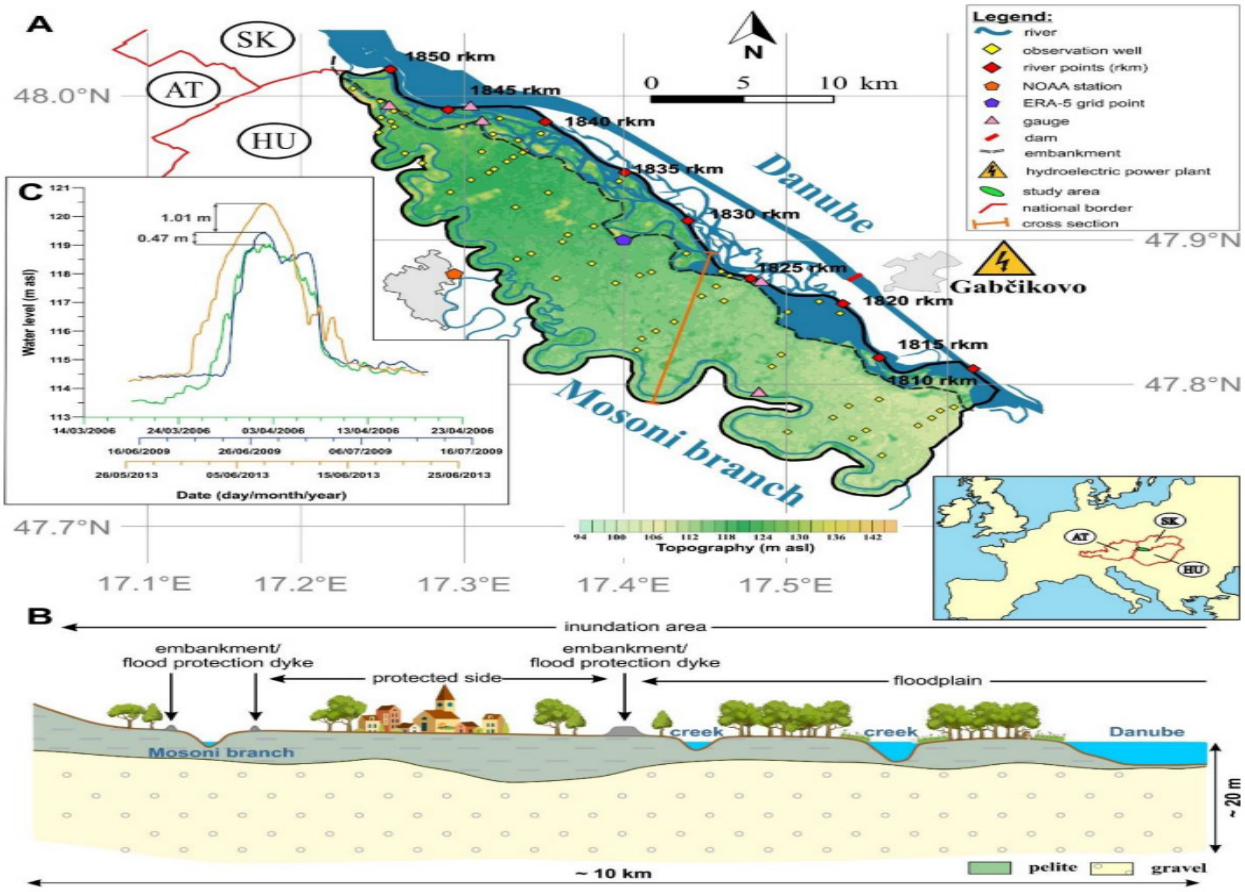



*Figure 2: Study area, the Szigetköz itself and its monitoring sites, along with the branches of the Danube and the "new" canal with the hydroelectric power plant at Gabčikovo. HU: Hungary, SK: Slovakia, AT: Austria. (Trásy et al., 2020).*

Today, only about 20%, or 250 to 350 $m^3/s$, of the pre-diversion yield flows down the original natural riverbed. Due to river regulation and dam construction, a steady water flow system has emerged in natural and artificial riverbeds, along with a river that experiences seasonal water level changes, measured in tens of centimetres. The drainage of the flood water from the upper sections of the Danube in Austria, however, causes brief increases in water levels in both riverbeds. Record flood occurrences (which may be more common in the future) cause significant, well-traceable changes in the original riverbed system that considerably impact GW monitoring systems in terms of both water quantity and quality.

Isotope-hydrogeochemical methods provide reliable insight when applied to study the subsurface flow conditions of the Szigetköz. These have generally focused on determining the origin, residence time, and flow velocity of the GW. Based on measurements of 36Cl and Tritium/3He, researchers found that

- the flow velocity within the Quaternary sandy gravel deposit series is 500–530 m/y
- the main flow direction is NNW-SSE
- the Danube River provides the main source to recharge the aquifer

## 1.4. Surface water – groundwater interaction

The surface water and groundwater interactions influence hydrogeological conditions in Szigetköz and play an essential role in the functioning of the wetland ecosystem. Some of the vital hydrogeological characteristics of Szigetköz include:

**River flow dynamics:** The Danube and Moson-Danube rivers are the main hydrological features in the region. Fluctuations in precipitation and seasonal changes in runoff drive their daily and seasonal variations in flow and surface water levels. These variations significantly impact groundwater flow direction and magnitude through the adjacent aquifers.

**Groundwater-surface water interaction:** The interaction between groundwater and surface water is a critical aspect of the hydrogeological conditions in Szigetköz. Groundwater is an important water source supporting wetland vegetation and maintains water levels in ponds, lakes, and marshes. Conversely, surface water can recharge the groundwater system and affect the quality and quantity of the groundwater.

Figure 4 summarizes the possible interactions between groundwater and surface water. Note that the interactions depend on the relative levels of both systems. Also shown in the figure is the hyporheic zone (discussed in section 1.4), where many biological, chemical, and physical exchanges occur.

Since the building of many observations well series between Rajka and Gyor, investigating the groundwater regime of the region has taken on greater importance. The Hungarian Northern Danube Regional Water Management Offices (EDUVIZIG) record them.

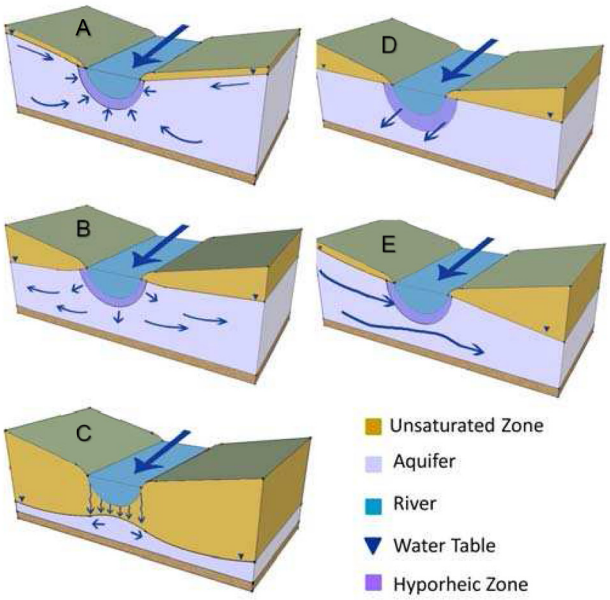



*Figure 3. Groundwater - surface water interactions: A) gaining, B) losing, C) disconnected, D) parallel, E) transverse.*

### 1.5. Additional Exchanges

In addition to hydrological transport, solutes, dissolved gases (oxygen, carbon dioxide, methane), biological actors, chemicals, and contaminants may all join the transport process, as shown schematically in Figure 4. Scientists name the hyporheic zone where exchanges occur between surface and groundwater.

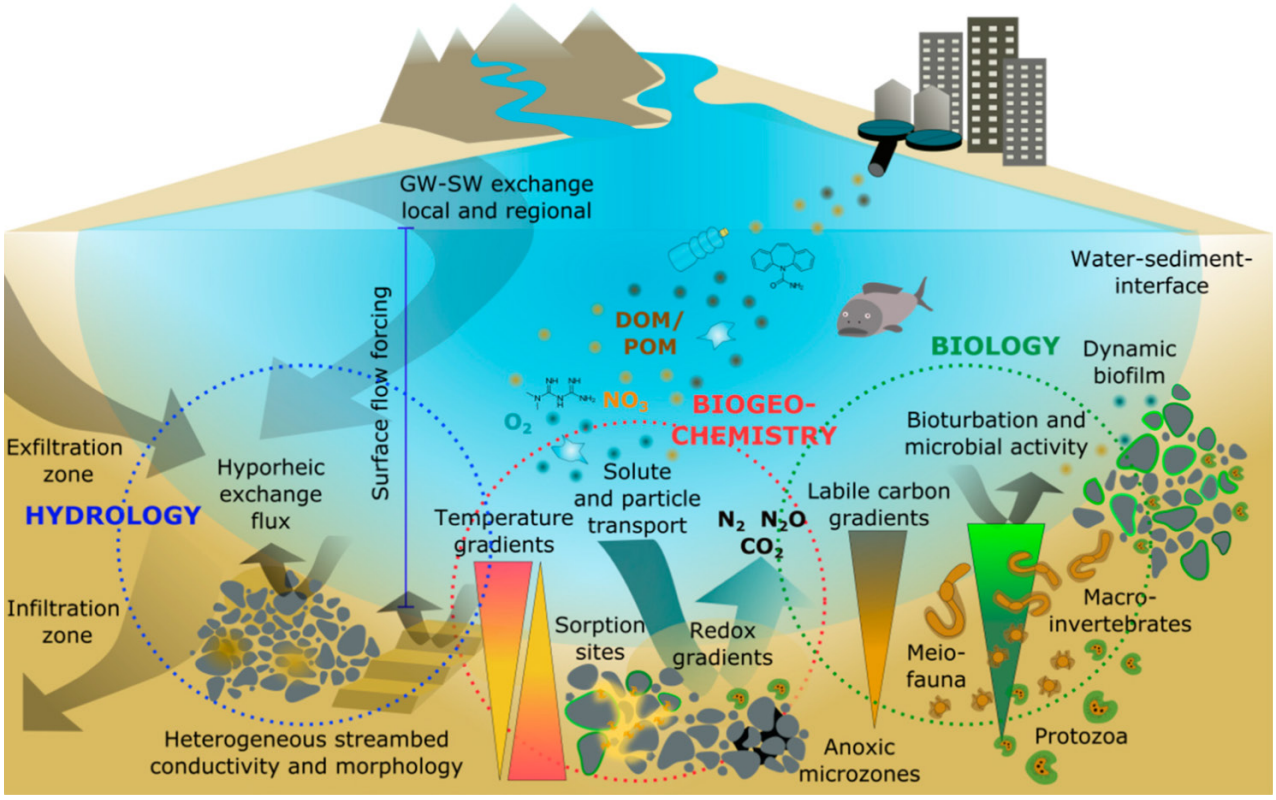



*Figure 4. Transport and exchanges that take place in a GW-SW environment.*

## 2. Preliminary analyses and considerations

In order to verify the unsaturated flow modeling procedure, a series of 1D analyses were performed on typical profiles found in the region using Hydrus 1D. The analyses allowed for familiarization with the numerical methods, verification of input data, and general confirmation of results.

### 2.1. Input data

Soil profiles consisted of 1 to 3 m depth with a single soil type and plant cover (root uptake). The VanGenuchten formula provided a numerical relationship between the matric suction and soil water content (Soil-Water Characteristic Curves, SWCC). The VanGenuchten-Mulaem method provided estimates of unsaturated hydraulic conductivity. Initial water content was assumed to be a linear function of matric suction with depth, where the profile's base (top of the water table) had zero suction. The profile surface matched its elevation from the base, i.e., if the profile was 100 cm high, the suction at the surface was (-100 cm) water. Evapotranspiration estimates resulted from meteorological data such as solar radiance, average wind speed, relative humidity, and maximum and minimum temperature. Finally, the Penman-Monteith model estimated the root water uptake for selected perennial grasses or seasonal crops (corn, wheat).

### 2.2. Rainfall

Since the analyses lasted one year, daily rainfall records represented the driest, wettest, and average 365-day records from the weather stations nearest Szigetköz.

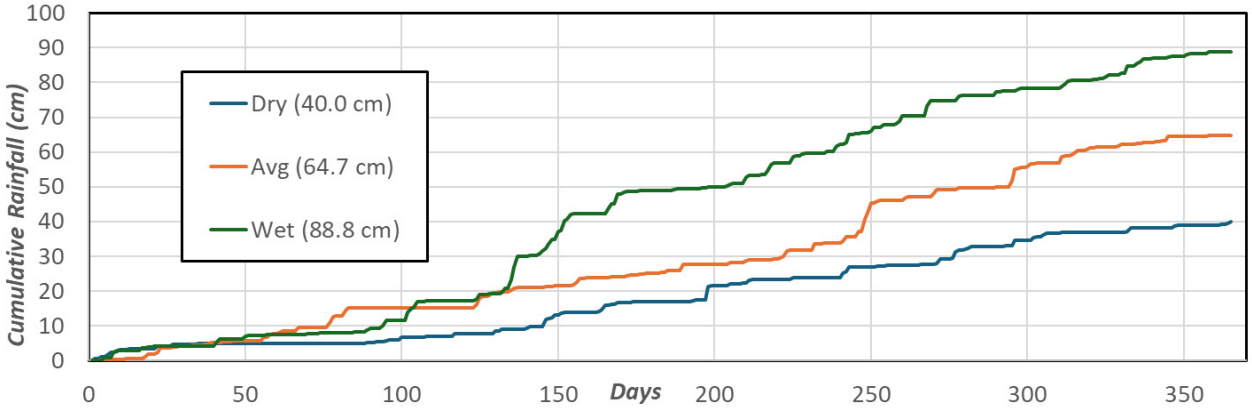
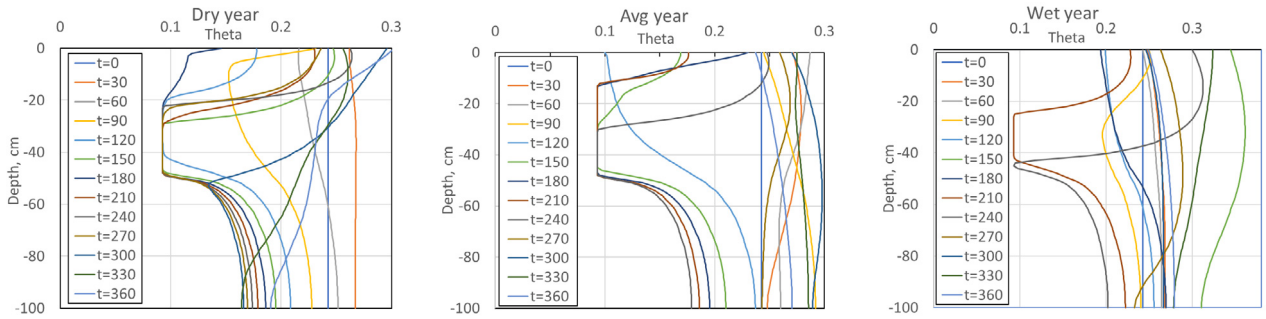



*Figure 5. Cumulative rainfall for preliminary analysis*

## 2.3. Results

Typical moisture profiles (moisture content [Theta] vs. depth) for the three rainfall conditions appear in Figures 6 a,b, and c. Each profile line represents one month. When comparing the three different annual rainfall conditions, the dry conditions (Figure 6a) show six months of dry soil (Theta = 0.1 at -20 to -50 cm depth) and only one month of wet conditions. For the average year (Figure 2b), two months showed dry conditions similar to the dry year, with two other months showing dry conditions for a smaller portion of the profile (-30 to -50 cm). The wet year (Figure 6b) also has one month of dry conditions, but the remaining months are relatively wet. These results are not intuitive because they are very different from a rainfall perspective but still present similar behaviour.



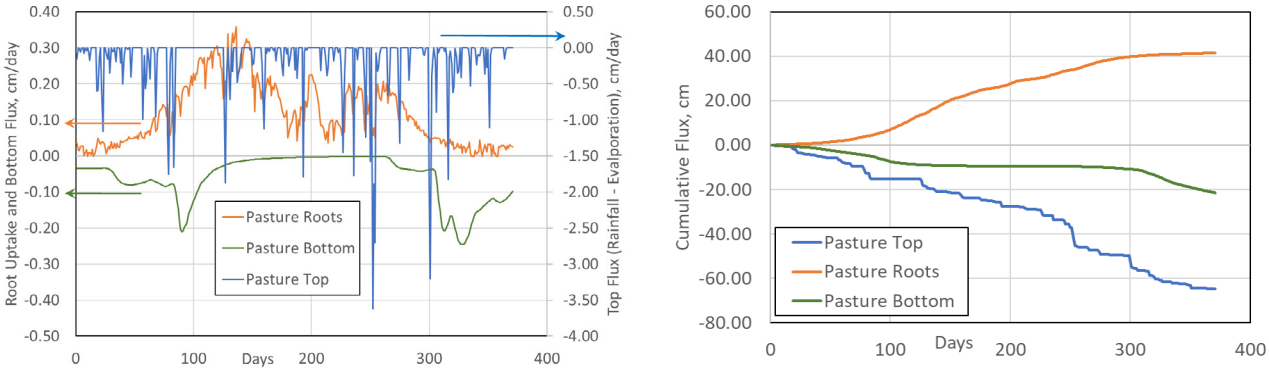

*(a)* *(b)* *(c)*

*Figure 6. Soil moisture (Theta) versus depth profiles for dry, average, and wet years*

The next part of the results concerns water flux into and out of the soil column. For a 1D profile near the surface, water can enter as rainfall, exit as evaporation, and exit from the root zone (usually near the surface) as transpiration. Water may enter from the groundwater table at the bottom of the profile if enough suction exists (the profile is dry), or if it is nearly saturated, exit as drainage (at least the lower part of the profile is saturated). If there is a downward flux (water exiting the bottom), the water will recharge the saturated groundwater system.

Figure 7a,b illustrates this effect, where the soil profile is similar to the previous examples, and pasture grass is growing at the surface. The graph indicates the downward (-) flux of precipitation from an average year, the upward flux (+) of root transpiration, and a downward (-) bottom flux indicating groundwater recharge. Note in Figure 7a the differences in response times where the top flux (blue) responds immediately to rainfall, and root uptake (orange) responds to daily solar radiation and seasonal changes. The bottom flux responds to the gradual shifts in water balance within the soil column. Figure 7b shows the long-term

behaviour where the cumulative recharge (green) reaches about 20 cm over one year. The recharge value is vital for estimating short-term and long-term water balance within the Szigetköz system. Different locations throughout the region will respond differently due to changes in topography, soil, and plant conditions.




*(a)* *(b)*

*Figure 7. Daily fluxes (a) for profile top, roots, and bottom and cumulative fluxes (b) for profile top, roots, and bottom*

# 3. Modeling with Hydrus 3D

## 3.1. Basic capabilities

HYDRUS is a finite element software package for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media (Šimůnek et al., 2018). The program numerically solves the Richards equation for variably saturated water flow and advection-dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. It may analyse water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The program can handle flow regions delineated by irregular boundaries, anisotropic properties, and various boundary conditions. The flow region may be composed of non-uniform soils with an arbitrary degree of local anisotropy.

Additional modules allow for specialised modelling.

Dual permeability soils that mimic preferential flow paths

Wetland modelling for biochemical transformation and degradation

Colloid transport and solute transport together

Multiple chemical component transport

These modules would apply to many situations mentioned in section 1.5, where transport and reaction processes occur.

## 3.2. Scale considerations

The most recent version allows for up to 10 million elements; practically speaking, computation time limits the program model, not the problem scale. The large scale is perhaps the most challenging aspect of developing a comprehensive model for a domain the size of Szigetköz. Given the domain area of 300 km$^2$, a 10 m by 10 m grid size translates immediately to 3 million elements. The only way forward would be to use a non-uniform grid where less critical locations would have larger discretisations. Other approaches include

segmenting the region into smaller regions with properly connected interfaces. Segmentation has been a helpful approach for other large-scale numerical models. Another approach is to reduce dimensionality whenever possible. This approach has been applied with the Hydrus1D add-on for Modflow. The 3D saturated groundwater flow model has a surface element applied to a (relatively) large area that performs computations similar to those in section 2.

Scaling up also requires a more robust workflow for generating time- and space-dependent boundary conditions and methods to handle post-processing.

# 4. Conclusions

The Szigetköz region is a complex network of surface and groundwater movement. This network is the underlying support for the diverse and valuable ecological systems that thrive there. Anthropogenic factors have impacted much of the region, often with adverse outcomes. However, improvements have been introduced and continue to benefit the usefulness and sustainability of the region. One of the long-term components of the program for improvement is the development of a robust, practical, and scalable groundwater model. Preliminary work has already been started and should reach its first stage of operation within a year. Challenges include data analysis, model verification on pilot scales, and adapting it to solve various hydrological and environmental problems.

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# ARTIFICIAL INTELLIGENCE IN HUMAN RESOURCE MANAGEMENT FOR SUSTAINABILITY: RESEARCH MAPPING BETWEEN 2002-2024

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The rise of artificial intelligence is driving leaders in organizations to change their perspective, which requires a rethinking of human resource management dimensions and poses challenges for employers and employees. The paper examines how Artificial Intelligence contributes to sustainable employer-employee relationships in human resource management. In a hybrid corporate reality, where human-machine interactions can be identified, neither the machine nor the human factor can be excluded if we want to understand real-life dilemmas. In our exploratory research, sustainability can be understood as a win-win situation between employer and employee, which lays the foundations for successful cooperation in the future for both parties. This study analyzes HR and AI-focused research, how they contribute, and in what field they are focused. With the requirement of sustainability, our goal is to recognize areas where AI can contribute to improving HRM processes. In this research, we examined 75 papers published between 2002 and 2024, which resulted from a search for HR and AI keywords in the Web of Science database. Based on our literature research and keyword density analysis, after determining the research gap, our goal is to map possible research areas. By focusing on the role of AI in human resource management, we highlight how AI can contribute to the sustainability of the employer-employee relationship.

## 1. Introduction

In the wake of Industrial Revolution 4.0, there was an increased need for changes in the social and economic sphere. Disruptive technologies, such as artificial intelligence [AI], Internet of Things [IoT], cloud-based technologies, and Big Data, have come into focus in the lives of companies. AI, which has been constantly evolving since the 1950s (Böhmer and Schinnenburg, 2023), is present in all areas of organizational life, as it is used in healthcare (Cavanagh et al., 2023; Li et al., 2023), in marketing (Liu-Thompkins et al., 2022) and other management disciplines (Prikshat et al. 2023). As a result, its role in the hybrid corporate reality has become unquestionable (Khatri et al., 2020; Jatobá et al., 2023). There is no consensus in the literature about the concept of artificial intelligence in our research; following Khatri et al. (2020), AI refers to Big Data-based technology that perceives, analyses, learns, and executes using algorithms. In the broadest sense, we define

it as "computational systems that involve algorithms, machine learning methods, natural language processing, and other techniques that operate on behalf of an individual" (Hancock et al., 2020, p. 89).

The rise of AI encourages leaders of organizations to change their perspective, which requires the rethinking of the dimensions of human resource management and thus poses challenges for both employers and employees (Trocin et al., 2021; Malik et al., 2022). With the development of AI, algorithms, automation, and the role of digital tools in the life of companies has increased. Numerous authors (e.g., Khatri et al., 2020; Hmoud, 2021) found the positive impact and efficiency of AI in the daily operations of companies, especially when performing time-consuming and complex tasks (Jatobá et al., 2023). At the same time, the downside is that constantly evolving AI threatens the work of human resources [HR] professionals, as it is already capable of taking on routine and cognitive tasks. AI-based systems can be adapted in all areas of human resource management, from developing human resource strategies (Jatobá et al., 2023), recruitment (Kelan, 2023; Malin et al., 2023), talent acquisition (Sattu et al., 2024), decision making (Radonjic et al., 2024), learning and development (Sithambaram and Tajudeen, 2023), performance management (Varma et al., 2024), data analysis and administration (Sithambaram and Tajudeen, 2023), issues of mental health and well-being (Dutta and Mishra 2023) to exit prediction (Chowdhury et al., 2023) and employee offboarding and exit management (Pillai and Sivathanu, 2020; Deepa et al., 2024). Despite its use throughout the employee lifecycle (Brown 2024), few HR professionals employ it, which may be due to their vague and poor knowledge of artificial intelligence (Malin et al., 2023). However, in a hybrid corporate reality where human-machine interactions can be viewed as a complex system, neither the machine nor the human factor can be excluded if we want to understand real dilemmas and want to ensure a sustainable relationship. Further development is required for both human and machine factors, so companies need to re-evaluate their operations to integrate AI effectively and sustainably (Khatri et al., 2020; Thite and Iyer, 2024).

Building on these theoretical assumptions, the aim of the study in the field of human resource management is to examine how artificial intelligence contributes to sustainable employer-employee relationships. The examination of sustainable human resource management has increased in value (Pongrácz and Rákosi, 2023). In this research, sustainability is understood as a win-win situation between employer and employee, which lays the foundation for successful, long-term cooperation in the future for both sides. This includes creating a work environment that supports employee well-being, satisfaction, and professional development while providing the company with a sufficient number of stable and committed workers (Ehnert, 2009; Dutta et al., 2023). The aim of the research is to examine the areas where AI can contribute to improving HRM processes, taking sustainability into account, and uncover the dilemmas arising from the uniqueness of the human factor. In this article, we examined 75 articles published between 2002 and 2024 that are listed in the Web of Science database for HR and AI keywords. Based on our literature research and keyword density analysis, i.e., after identifying the research gap, possible research areas were mapped. By focusing on the role of AI in human resource management, the study shows how AI can contribute to the effective sustainability of the employer-employee relationship.

The results of the study can contribute to the work of researchers, HR professionals, and managers by exploring connecting areas where artificial intelligence can play a decision-making role. By identifying the application areas of AI, the study contributes to the more efficient and effective operation of these segments. Furthermore, the novelty of the study is that is places sustainability in a new context, in which we examine it in relation to the employer-employee relationship, focusing on employee well-being. The novelty of the findings is that the study highlights those areas where AI can contribute to the sustainability of the employer-employee relationship, leading to more efficient human resource management in the long term.

# 2. Method and results

The methodology of our research and the results are elaborated below. The presentation of the results is divided into two subsections, emphasizing artificial intelligence's important role in recruitment.

## 2.1. Method

Our study, with the objective of providing a comprehensive picture of human resource management in the areas whose efficacy is being explored in research with the assistance of artificial intelligence, is thorough

and in-depth. During the background discovery phase of our investigation, we utilized Mueller-Bloch and Kranz's (2015) method to identify a gap in qualitative research. The framework consists of four components, of which this study is the first stage, that is, the initial stage, the localization of the research niches, which was aimed at revealing the research areas in this paper, thereby highlighting the gaps. Our query in March 2024 revealed 75 researchers from the field of Business Management for the keywords human resource and AI. However, the fact that our new query in May already contained 96 publications for the same keywords is a testament to the holistic perspective we are taking in this paper.

## 2.2. Results

After removing research that is not relevant to this study (21), 75 publications were analyzed. First, we performed keyword density analysis with VosViewer to further delineate the areas studied by the researchers, which is clearly shown in Figure 1. During the keyword density study, identical terms such as artificial intelligence and artificial intelligence were merged for transparency. The basic settings of VosViewer were used to create the figure, and the strength of the keyword occurrences is four. Considering the number of occurrences is important because when analyzing keyword networks, keywords that occur more often can have a greater impact on the structure of the network, as shown in the figure below. We excluded keywords that do not refer to the field of science but refer to the nature of the research, such as literature review.

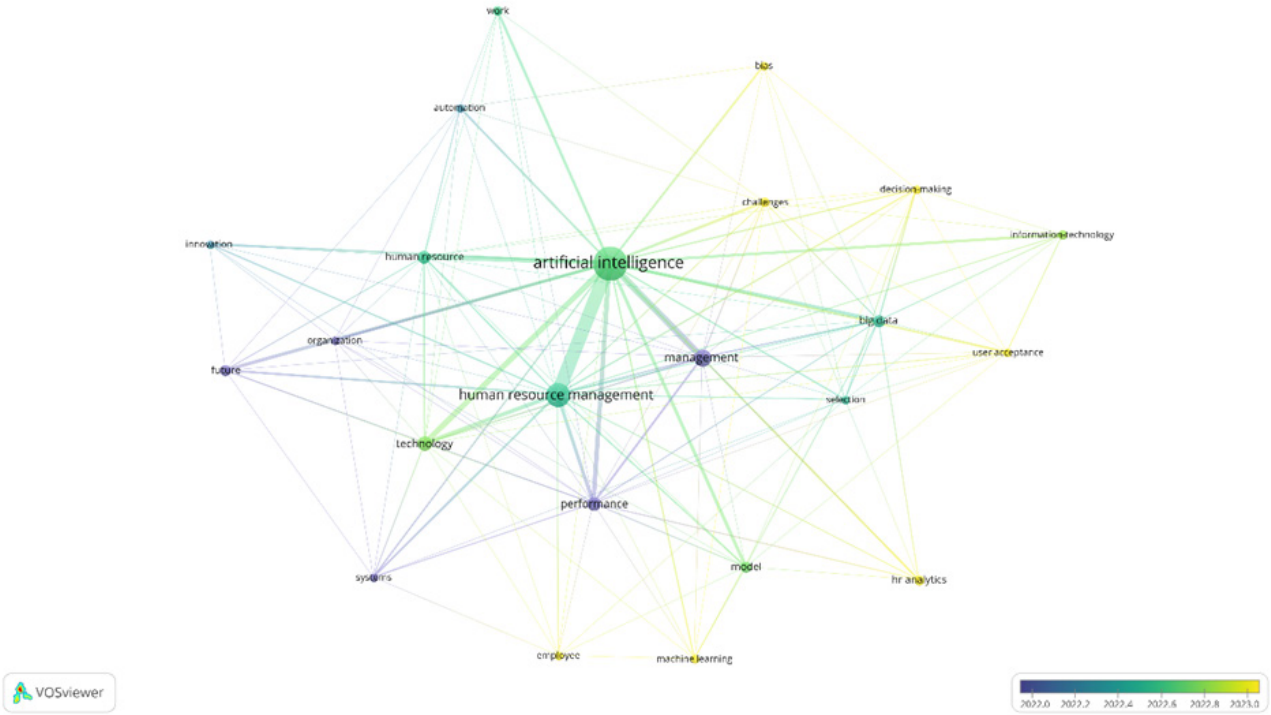


*Figure 1: Overlay Visualisation by VosViewer (keyword co-occurancies 4) based on Web of Science database search for the „Human Resource Management" and AI keywords*

The examined papers which met the requirements of the settings were published in 2022 and 2024. The figure clearly shows that in 2022 research focused mainly on organizations and their performance and their future, then on issues of innovation and automation, and recently researchers have been interested in decision support, challenges, and biases.

In the following sections, we will present a detailed analysis of the focus areas of the selected publications and research studies. This will include an in-depth examination of the specific topics and key findings within the field. Our aim is to underscore the central problem spaces and trends that emerge from the literature, which will provide a comprehensive overview of the current state of research and its implications for future

studies. By doing so, we start the initial phase to identify research gaps in the existing publications and suggest potential focuses for further investigation.

Artificial intelligence is transforming traditional HRM processes and thus both HR functions and roles (Malin et al., 2023). AI offers great opportunities to support HR professionals by providing them with an AI-assisted toolkit (Hmoud, 2021; Jatobá et al., 2023) that allows them to complete time-consuming and routine tasks more efficiently (Hmoud, 2021; Radonjic et al., 2024). Sithambaram and Tajudeen (2023, p. 821) confirmed in their research that "AI usage in HRM could generate operational, managerial, strategic, organizational, informational and compliance benefits for companies". This is confirmed by Jatobá et al. (2023), who identified three main areas of use of artificial intelligence in their research: strategy, recruitment, training. Furthermore, the literature review has confirmed that its application in HRM covers the entire employee life-cycle: human resource planning, recruitment (Böhmer and Schinnenburg, 2023), selection (Malin et al., 2023), talent management (Pillai and Sivathanu, 2020; Sattu et al., 2024), performance management (Varma et al., 2024), training (Sithambaram and Tajudeen, 2023), personalized employee experience (Malik et al., 2022), employee exit (Prikshat et al., 2023; Deepa et al., 2024). Its broad inclusion can reduce turnover, increase satisfaction and increase commitment (Malik et al., 2022), thus contributing to a sustainable employer-employee, win-win based relationship.

### 2.2.1 The use of AI in recruitment based on the literature

Despite its advantages, the use of AI in the recruitment process is low (Malin et al., 2023), although it can support almost every step of it. By providing process support in creating recruitment strategies (Mohamad et al., 2022; Böhmer and Schinnenburg, 2023), workforce planning, reviewing CVs (Tsiskaridze et al., 2023; Varallyai and Hmoud, 2023), analyzing or even conducting interviews and connecting with candidates via chatbots (Kim et al., 2024; Sattu et al., 2024), AI can save HR professionals time and costs (Stone et al., 2024). Furthermore, the use of AI requires companies to adapt to a rapidly changing economic environment and the needs of applicants and employees to achieve sustainable competitive advantages. However, AI is used to a limited extent for decision support, as it mainly plays a role in the provision and collection of information, candidate search and matching, and selection in the recruitment process (Malin et al., 2023). Some researchers (Oswal et al., 2021; Mohamad et al., 2022) found that AI in recruitment can lead to more accurate and unbiased selection and more effective talent acquisition, less gender discrimination, and a more personalized process (Kim et al., 2024). However, other researchers (Soleimani et al., 2022; Michelotti et al., 2024) noted a number of ethical concerns, such as algorithmic bias, lack of transparency, impersonality, data privacy, or potential loss of human oversight (Varma et al., 2024), which could hinder the adoption of AI in HR processes.

### 2.2.2 The use of AI in talent and performance management based on the literature

AI can also be integrated into other onboarding and talent management processes (Mohamad et al., 2022; Varallyai and Hmoud, 2023). At the same time, it can be seen from the literature review that its role in training and development is being pushed into the background (Dutta and Poyil, 2024), although it represents one of the foundations of a sustainable employer-employee relationship, such as the lack of adequate training and development opportunities reduces engagement and satisfaction (Brown, 2024).

Based on the literature review, it can be stated that performance management systems are the other main application area of AI in HRM, along with decision support in recruitment and selection. Varma et al. (2024) examined the advantages and disadvantages of using this system and found that AI can speed up this process, goals can be more customized, and employees can open up more easily through the use of chatbots (Dutta et al., 2023), making the reasons behind their performance easier to understand. However, disadvantages were also identified that are consistent with the ethical dilemmas discussed previously.

In the context of improving performance, as digitalization in the workplace increases, AI and other disruptive technologies will become increasingly important in improving employee experience and engagement in HR practices. In their research, Dutta et al. (2023) found that AI-enabled chatbots also play a motivating role, and based on their results, there is a positive correlation between these tools and engagement. AI enables

the personalization of HR processes to increase individual motivation and performance, providing the workforce needed for sustainable competitive advantage. These include personalized HR-related recommendations, HRM options for employees to choose from, and individualized HRM programs (Huang et al., 2023).

AI-driven advanced HR analytics systems are increasingly being integrated into individual performance measurement in addition to recruitment (Sadler-Smith et al., 2022). AI helps optimize employee performance by analyzing individual data and setting personalized performance goals (Huang et al., 2023; Xiao et al., 2023). Data collection can be used to create detailed reports on employees and make recommendations to improve their performance using the forecasting function (Marabelli and Lirio, 2024). The decision-supporting role of AI is also evident here, as AI-driven HR analysis systems are needed to explore the interfaces between individual HRM activities (Cavanagh et al., 2023).

Overall, AI and other disruptive technologies have time- and cost-reducing benefits in HRM processes, but AI cannot replace or support HR professionals in achieving a sustainable employer-employee relationship. Human-machine collaboration is required to develop an effective HRM system (Xiao et al., 2023), in which the decision-supporting role of AI can be even more prominent.

# 3. Conclusions

The sustainable employer-employee relationship in this research is meant to be a long-term, trust-based cooperation. In a sustainable environment, the employer's goal is to support employee well-being, including mental and physical health and development. Based on the literature research, it can be concluded that the AI's contribution to this sustainable relationship lies in enabling personalization and proactive support of employee needs, thereby ensuring a sustainable work environment.

Artificial intelligence (AI) has transformed human resource management (HRM) and digital technologies in enterprises, offering a range of possibilities. AI enables the implementation of HR strategies, talent acquisition, decision-making, learning, and performance management. It can bring significant benefits in areas such as recruitment, employee offboarding, exit prediction, and mental health and well-being. However, AI also faces challenges, including algorithmic bias, lack of transparency, impersonality, data privacy, and the risk of human control loss. As AI and human capabilities evolve, businesses must strike a balance in their processes to integrate AI in a manner that is both suitable and sustainable.

Artificial intelligence has the potential to optimize operations that require a significant amount of time, reduce employee turnover, and increase employee engagement, resulting in a link that is mutually beneficial for both employers and employees. It is also possible to include AI in the processes of talent management and onboarding, although individuals typically need to pay more attention to the requirements for training and development. Modern human resource analytics systems analyze individual data and make use of chatbots that are equipped with artificial intelligence in order to motivate and optimize staff performance. This is done in order to improve employee performance. The development of a human resource management system that is both sustainable and effective requires collaboration between humans and machines, with artificial intelligence playing a more major role in decision support functions.

In this study, we examined only a single database and focused on Business Management. Further investigations in other databases are necessary to gain a more accurate understanding of AI applications, potential uses, and research in Human Resource Management (HRM). This additional research can provide a more comprehensive understanding and identification of AI applications in HRM.

Based on the analyzed literature, several future research directions can be formulated. Although in this research we have touched on the ethical concerns of AI, deeper analyzes are needed to explore the issue of algorithm biases and data privacy. With the help of corporate partners, we will review what AI tools they use in the HRM processes and how, with particular regard to data protection, ethical questions and the interpretation of sustainability. In addition, it is important to examine the role of AI in other key HRM processes (e.g. talent and performance management, personalization, training and development), and assess the effectiveness and accuracy of the AI tools. Also, a deeper examination of the collaboration between human and artificial intelligence in decision-making is definitely justified.

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# SUSTAINABLE PLANT NUTRITION OF WINTER WHEAT

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A sustainable economy focuses on minimising the generation of waste and tries to protect and maintain the materials used in the economy. The by-products and waste used in plant nutrition can help with this. In small-plot experiments set up in 2020 and 2021, the effect of two substances on winter wheat was examined. One of the used materials is Vinasse, which is a by-product of alcohol production, and the other is a zinc complex, which is produced from scrap metal. The chemical substances were used as foliar fertilisers, and their effect on the yield, crude protein and gluten content of winter wheat was examined. The impact of these formulations was examined when applied as foliar fertilisers separately and together at doses of 50, 100, 250 and 500 L/ha for Vinasse and 0.5 kg/ha for zinc complex. Based on the results of the small-plot experiments set up in the fall of 2020 and 2021 and harvested in the summer of 2021 and 2022, it can be concluded that using Vinasse and zinc complex treatments, a higher yield and better content indicators could be achieved compared to the control plots. The highest dose of Vinasse (500 L/ha) and zinc complex (0.5 kg/ha) had the greatest positive effect on yield values. Regarding the plot yield, the treatment did not bring a significant correlation, while the effect of the treatment was found to be significant at 1 % for the protein content, and an even stronger significance level of 0.5 % was found for the gluten content of winter wheat samples in 2021 and 2022. So, it can be concluded that our treatments had an effect on the quality of the crop rather than its quantity.

## 1. Introduction

Winter wheat (*Triticum aestivum* L.), which is one of the world's most valuable and widely cultivated cereals, has a production area of around 245-250 Mha worldwide. Its importance as food in the world can only be compared to rice. Its widespread was made possible by the diverse climatic needs and good adaptability of wheat varieties and varieties (Radics, 2007).

Wheat is used for food, mainly in the form of flour. The method of its use is very diverse; they mostly make bread from it, but apart from bread, there are many other ways of use in the baking, pasta and confectionery industries. The multifaceted use is also supported by the fact that wheat is a high-quality fodder, and its by-products are also valuable. Apart from corn, winter wheat is the most important field crop in Hungary. It had 947,300 ha in 2022, 1,033,300 ha in 2023, and 874,600 ha in 2024. Examining the change in sown area for the last 10 y, we can see that it is around 1Mha in Hungary (KSH, 2024).

The structure of the plant body could be determined quite precisely with plant analyses carried out using different methods. These elements are usually grouped in various ways based on their quantity and role in the plant. As early as 1957, Vinogradov suggested that the amounts should be used as a basis for the division of nutrients. The elements occurring in larger quantities are called macro elements (N, P, K, Ca, Mg, S), while the elements occurring in smaller quantities are called microelements (Fe, Mn, Cu, Zn, Mo, B).

The role of micronutrients is partially different from that of macronutrients, as they do not function as basic building blocks. They do not play a primary role in increasing crop yield, but based on their functional task, they are indispensable in plant biochemical processes, e.g. ensuring the smooth operation of enzymes (Győri, 1984). Due to possibly inhibited transport processes, their absence can often be detected even in plants grown in soils which are well supplied with copper and zinc. Knowing the soil composition, it is also possible to improve the quality in addition to increasing the yield by replacing the microelements showing a deficiency (Szakál et al., 2007). In small-plot experiments carried out in 2020-2021 and 2021-2022, two materials that meet the basic principles of circular farming were examined. These two substances were a zinc complex and the other was Vinasse, a by-product of sugar production.

From a biological point of view, zinc is one of the most important metal ions, and it is essential for all forms of life, actively participating in protein metabolism and plant growth regulation by stimulating auxin production (Kalocsai et al., 2005). Zn deficiency in soil can inhibit plant growth and development and thus inhibit plant yield and quality (Nie et al., 2023). The two best-known zinc-containing enzymes are carboxyl peptidase-A and carbonic anhydrase. Through the activation of peptidases, it also affects nitrogen metabolism (Alloway, 2009). Zinc (Zn) deficiency among humans is a worldwide problem, especially for those who rely on cereals as staple food (Welch and Graham, 2004). The low availability of Zn in soils and edible parts of crops is a key factor contributing to the widespread occurrence of Zn deficiency in humans (Liu et al., 2022).

Zinc ensures the stability of the membranes, without which the cells would "empty", i.e. the membranes would let everything through. Similar to copper and boron, due to a lack of zinc, the released substances (sucrose, aromas) attract plant-damaging microorganisms and pests to the leaves and also serve as food for them. Zinc also has demonstrated an antibacterial power (Dadi et al., 2021). Based on this, it can be said that supplementing plants with zinc is also a protection against diseases.

The forms and quantities of zinc available and absorbed by plants are relatively low values and are influenced by several factors (e.g. soil chemistry, lime content, phosphorus content) (Kalocsai et al., 2004).

Zinc supplementation is possible in two ways: through the soil and through the foliage. While nutrient supplementation through the soil is mainly determined by soil test results, the need for foliar fertilisation is often revealed by professional visual inspection of deficiency symptoms.

The absorption of nutrients by the young plant parts and leaves is also significant, in addition to the absorption of nutrients through the roots. Nutrients applied to the surface of the plant are absorbed directly and within a short time, and their effect is not dependent on precipitation. It is recommended to be used in cases when quick intervention is required in order to preserve the quality of the plant stand. Nutrient replenishment through the leaves of plants is effective but limited to a small amount (Kalocsai, 2010).

In Hungary, Rózsa et al. (2011) investigated the effect of the basic zinc carbonate complex on winter wheat. Their experiments proved that zinc positively influences both the yield and the quality parameters of winter wheat. The treatments significantly increased the yield, grain content and crude protein content of winter wheat. The dosage to achieve an optimal effect is a zinc dose of 1.4-1.6 kg/ha.

The zinc complex used in the experiments also embodies the transformation and recycling of waste. It is produced from zinc-tetramine-sulphate, which is a zinc-containing waste, by chemical transformation, and then it was made suitable for application as foliar fertiliser. Thus, it is ultimately used for nutrient replacement.

Plants can absorb zinc from the soil in the form of $Zn^{2+}$ ions or as a chelate-type organic compound. Almost 50% of the world's soils, which are suitable for growing cereals, are classified as potentially deficient in zinc. According to Kádár (2005), 46% of Hungarian soils are poorly supplied with zinc. Several factors influence the absorption of zinc forms that are available and can be taken up by plants (e.g. soil chemistry, lime content, phosphorus content) (Kalocsai et al., 2005).

Vinasse was used as the other experimental substance. In the first phase of beet sugar production, the by-product is molasses, which still has a high sugar content and is suitable for alcohol production. The secondary product processed during the production of molasses-based spirits is Vinasse. After the fermentation of the molasses, the spirit is extracted from the mash. The remaining material during distillation is

the molasses liquor with 8-10 % dry matter. This material is concentrated in a vacuum evaporator, which is marketed under the name Vinasse. This is a by-product, but it would be a mistake to think of it only as industrial waste since it can also be a possible means of nutrient replenishment.

Yeast vinegar is a dark brown, thick, viscous liquid with a characteristic smell. Thanks to the high dry matter content, the material is chemically stable and can be stored in its original state for years. It can be easily diluted, and it dissolves well in water.

In order to produce quality agricultural products, it is necessary to ensure the soil's ability to supply nutrients in accordance with the needs of the specific crop. Justus von Liebig's important statement is the main principle of circular farming in agriculture - "The soil must get back at least what the plant has taken from it" (Debruck and Lewiczki, 1996).

The carbohydrates in yeast vinegar increase the activity of nitrogen-fixing bacteria, thus further increasing the nitrogen available to plants. However, there is also potassium in yeast vinegar, in even greater quantities than nitrogen (5-7 %), which improves not only the growth and sugar synthesis of fruits but also the plants' ability to withstand stress. In addition, potassium is not bound to chlorine, which is an added advantage in many cases. As a complex biological substance, it also contains a range of essential microelements in addition to macroelements. Vinasse contains most of the macro (micro) nutrients that plants need, except for Co, Mo and Zn (Carpanez et al., 2022).

Vinasse is almost as old as sugar beet cultivation. Investigations related to its use began in the 19th century, but after that, those were forgotten. Those results were rediscovered in the 1970s in France and Germany.

As early as 1845, Justus von Liebig suggested the use of the by-product of alcohol production, which was still anonymous at the time, for the purpose of fertilising sugar beet fields, primarily to replace the missing potassium (Debruck and Lewiczki, 1996).

At the beginning of the 20th century, Vinasse became the generally accepted name for condensed, fermented sugar beet molasses in Europe.

Vinasse was already used in crop cultivation in the 1970s in the Győr area producer cooperatives. The first experiments served to reduce costs because even though the transport and spreading costs of Vinasse were relatively high, the total costs were still lower than the use of artificial fertilisers.

In the mid-1990s, the Faculty of Agriculture in Mosonmagyaróvár received an order from Győr Alcohol Factory and Refinery Co. in order to determine the utilisation of Vinasse in plant cultivation under domestic conditions.

The effect of Vinasse soil treatment in different amounts was investigated by researchers on five plant species: sugar beet, winter wheat, potato, pea and corn. The results were different for each plant species:

- For sugar beet: the white sugar yield of sugar beet could be increased by adding Vinasse;
- For winter wheat: the specific protein yield increased after Vinasse treatment;
- For peas: the seed yield increased significantly after the treatments;
- For maise: the treatment effect on grain yield and protein yield was significant;
- For potatoes: the number of tubers per hectare increased significantly after Vinasse treatments (Kajdi et al., 2000).

It can also be considered a valuable by-product in many areas of use, such as agricultural fertiliser, soil conditioner, and pest control additive and as a medium for microbial biomass production (Hoarau et al., 2018). In this regard, the varying concentrations of nutrients in these feedstocks result in Vinasse rich in compounds such as nitrogen, phosphorus, and potassium, which can be utilised in different biotechnological and agricultural processes (Gomez and Correz, 2024).

Barkóczi et al. (2007) examined the advantages and disadvantages of the agricultural use of Beeswax and found that Beeswax had a favourable effect on plant nutrition due to its high potassium content. However, the high sodium content found in Vinasse had a negative effect, which helped salt accumulation and compaction in the upper layer of the soil of the investigated area.

# 2. Material and method

In Hungary, several experiments were conducted on different plant species with Vinasse as a foliar fertiliser. Plant nutrition experiments with both Vinasse and zinc are being carried out in several countries around the world. Zinc foliar fertilisation is also known, but there is no data yet on the combined use of the two substances as foliar fertilisers. Our hypothesis was to examine the effect of different doses of Vinasse on our small plots of winter wheat as well as the impact of foliar fertilisation with zinc complex in a separate treatment, and finally, to examine whether there is a synergistic effect between the two substances. The question was whether the amino acid content of Vinasse could favourably affect the plant's ability to absorb zinc at the leaf tip. The research site was the Experimental farm of Albert Kázmér Faculty of Agricultural and Food Sciences of Széchenyi István University. The used winter wheat variety was (*Triticum eastivum* L.) Mv. Nádor.

## 2.1. Characteristics of the experimental area

The soil type of the production area is Danube alluvial soil. The thickness of the soil layer that could be taken into account in the experimental area calculation is about 120-140 cm. The soil has a lime content of 16-18 %, a low salt content, and a neutral pH (7.30-7.55). Its humus content can be considered as good (2.5-3.0 %).

## 2.2. Climatic characteristics of the experimental area

The experiments were also influenced by meteorological factors. The climate of the area is a temperate, humid continental type. The average annual temperature is around 11 °C. The data for the experimental area came from the meteorological station in Mosonmagyaróvár, operated jointly by HungaroMet (former National Meteorological Service) and the Széchenyi István University, and it is situated in the Experimental farm area.

The average temperatures of the time intervals of 2020-2021 and 2021-2022 were compared with the 30-year (1990-2020) average temperature values during the winter wheat growing season. The winter months were milder in both years (2021 and 2022), the spring months were slightly cooler, and the summer was warmer than the long-term average. Based on the analysis of the HugaroMet, the average annual temperature in Hungary in 2022 was 11.8 °C, which was 1.1 °C higher than the 1991-2020 climate normal value. The annual average temperature in Mosonmagyaróvár was 12.0 °C in 2022.

The average of the yearly precipitation sums for the last 30 y (1991-2020) was around 580 mm in Mosonmagyaróvár. An annual precipitation sum could be measured that was close to the long-term average in 2020 (582.5 mm), but in 2021, it was slightly below the thirty-year average (548.5 mm). In 2022, only 511.5 mm of precipitation fell in Mosonmagyaróvár.

## 2.3. Features of the experiments

Small plots of arable land were set up to analyse the impact of Vinasse and zinc-complex foliar fertilisers. The experimental layout was a randomised block with four replications; the size of each experimental plot was 10 m². Winter wheat was sown on 10.15.2020 and 10.14.2021 and harvested on 7.7.2021 and 7.4.2022, respectively. The treatments and foliar fertilising were carried out with a hand sprayer when the winter wheat was in the stem elongation phase: 05.06.2021 and 04.14.2022.

### 2.4. Treatments, examinations

After mechanical harvesting of the small-plot plant stands, a 1 kg sample was taken from each plot, which formed the basis of further tests. After harvesting, the plot weight was measured from which the yield of the given treatment could be deduced. The crude protein and wet fat contents of the samples were examined with the Perten Inframatic 9200 Grain Analyser under non-destructive conditions at the Department of Water Management and Natural Ecosystems. The analyser used during the measurement performed the measurement in the near-infrared range (NIR), between 1100-1400 nm, based on the principle of transmission. The treatments of the experiment were as follows:

1. Control: these plots did not receive any foliage fertiliser;

2. Nitrosol 28 % N-content liquid fertiliser 100 L/ha: this is a foliar fertiliser generally used by farmers, and it made possible to compare the effect of this foliar fertiliser on winter wheat with the other products;

3. Zinc complex 0.5 kg/ha;

4. Vinasse 50 L/ha;

5. Vinasse 100 L/ha;

6. Vinasse 250 L/ha;

7. Vinasse 500 L/ha;

8. Vinasse 50 L/ha + Zinc complex 0.5 kg/ha;

9. Vinasse 100 L/ha + Zinc complex 0.5 kg/ha;

10. Vinasse 250 L/ha+ Zinc complex 0.5 kg/ha;

11. Vinasse 500 L/ha+ Zinc complex 0.5 kg/ha.

## 3. Results and their evaluation

The values shown in the diagrams are the averages of the data measured in four replicates of the different treatments. The significance of the treatments was examined with the t-test. The conditions required to conduct a t-test include the measured values in ratio scale or interval scale, simple random extraction, homogeneity of variance, appropriate sample size, and normal distribution of data. The F-test was used to compare the variances of the samples. Figure 1 shows the effect of different treatments on winter wheat yield. It can be seen that the high-dose Vinasse treatment supplemented with zinc complex gave the highest yield value in both years. After performing the t-test, it could be found that the difference in the averages in both experimental years was significant at P = 5 %.

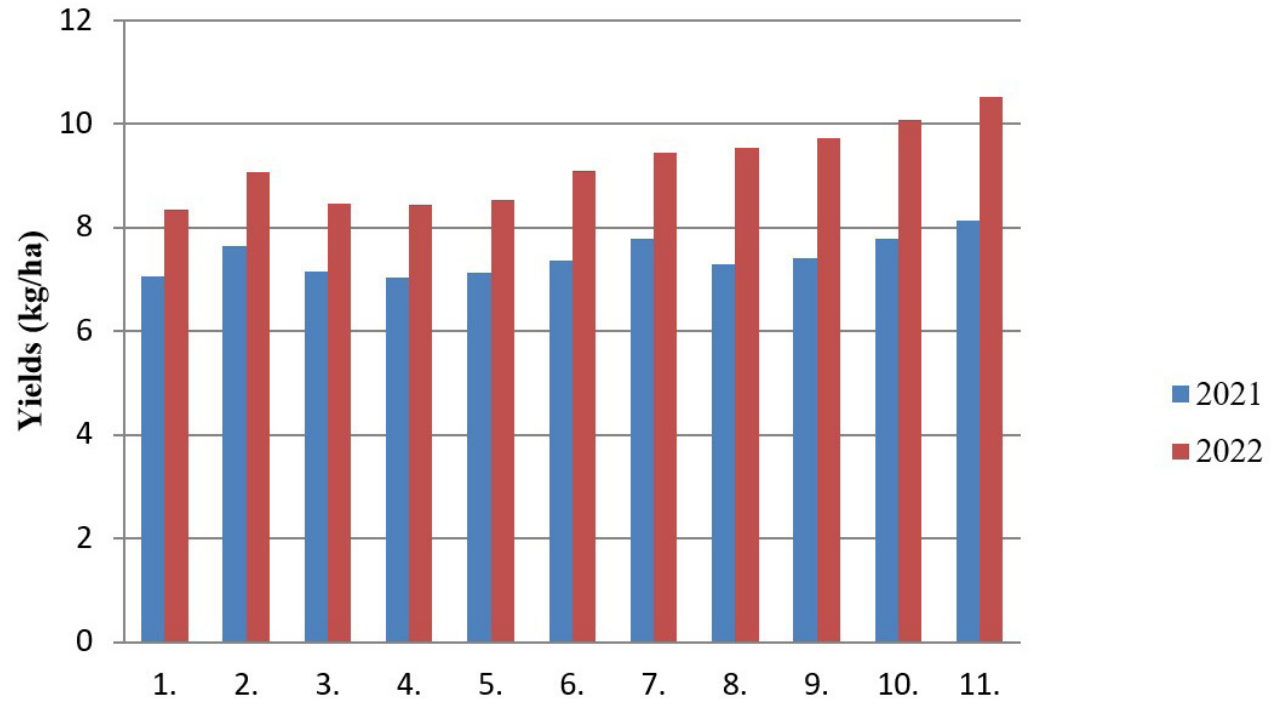


*Figure1: Yield of winter wheat plots in 2021 and 2022*

Figure 2 shows the effect of different treatments on the crude protein content of winter wheat. In the experiments conducted in 2021 and 2022, all treatments resulted in a higher crude protein content compared to the control. As a result of higher doses of Vinasse and zinc complex treatments, the highest crude protein content could be obtained. Performing the t-test on the averages, it was found that the 10-th treatment (Vinasse 250 L/ha and 0.5 kg/ha zinc complex) was significant at P=5 %, while the 11-th treatment (Vinasse 500 L/ha and 0.5 kg/ha zinc complex) was significant at P = 1 % in both experimental years.

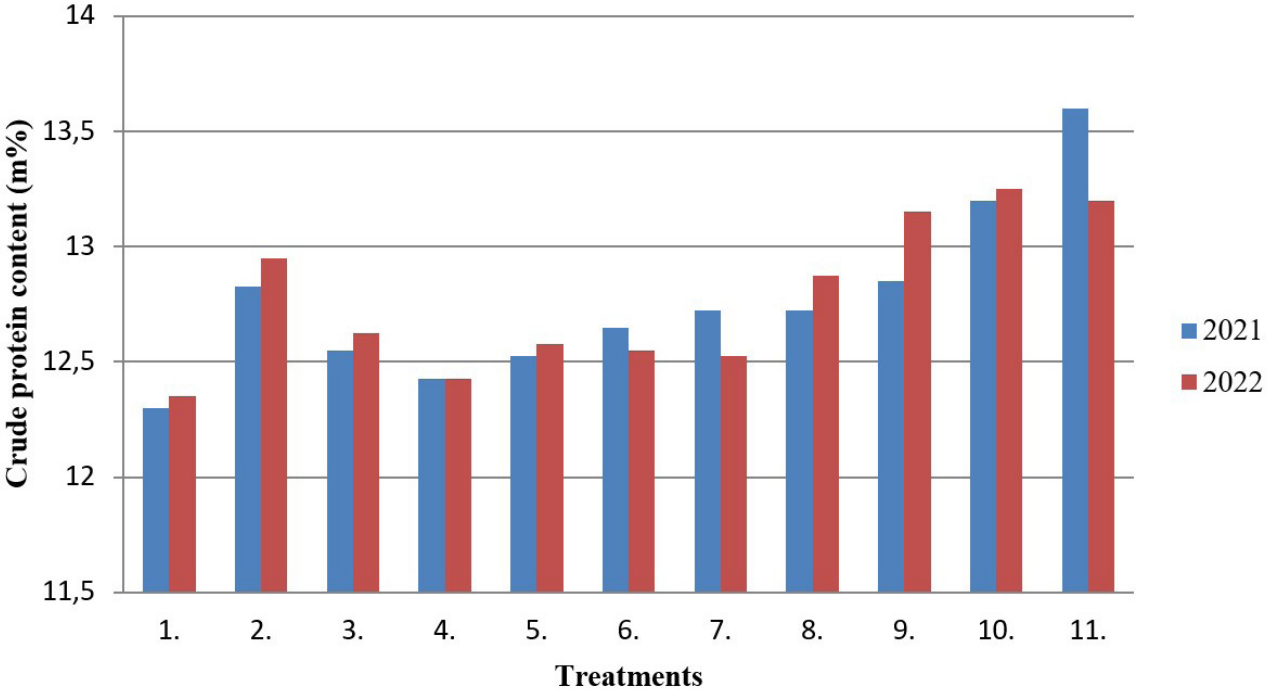


*Figure 2: Crude protein content of winter wheat samples in 2021 and 2022*

One of the most important quality indicators of wheat is its wet gluten content. The gluten is due to the combination of gliadin and glutenin in wheat grains. Gliadin gives wheat flour elasticity and stickiness, while glutenin gives it strength and resistance. In Figure 3, the effect of the different treatments on the wet gluten content can be seen. Also, in the case of this quality indicator, the treatment with Vinasse and zinc complex resulted in the highest values, but it is noteworthy that the foliar fertilisation with only zinc complex also exceeded the content values of winter wheat grown on untreated plots.

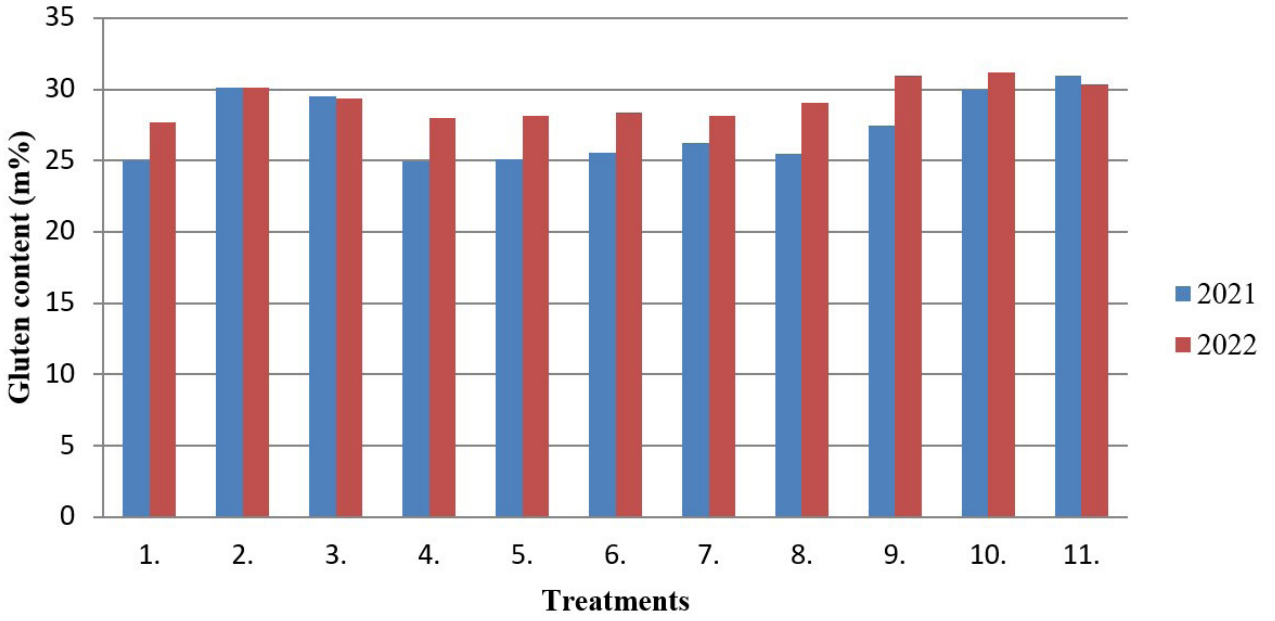


*Figure 3: Gluten content of winter wheat samples in 2021 and 2022*

The t-test on the averages of the gluten content was also performed, and for these values, the highest level of significance was obtained in both experimental years (P= 0.1%). Therefore, the deviation of the averages of the wet gluten content compared to the control values is significant at the highest level.

# 4. Summary and conclusions

Based on the results of the small-plot experiments set up in the fall of 2020 and 2021 and harvested in the summer of 2021 and 2022, the conclusion could be drawn that a higher yield and better quality indicators could be achieved with Vinasse and zinc complex treatments compared to the control plots. The highest dose of Vinasse (500 L/ha) and zinc complex (0.5 kg/ha) had the greatest effect on yield values.

The crude protein content was increased with the highest value compared to the control due to the high dose of Vinasse and zinc complex. After performing the t-test on the averages, it could be found that the 10th treatment (Vinasse 250 L/ha and zinc complex 0.5 kg/ha) was significant at P=5 %, the 11th treatment (Vinasse 500 L/ha and zinc complex 0.5 kg/ha) was significant at P=1 %.

In the winter wheat experiment, the gluten content of the plots was also increased to the greatest extent by the high-dose foliar treatment 11 (Vinasse 500 L/ha and zinc complex 0.5 kg/ha). The highest level of significance (P=0.1 %) could be obtained for these averages, so the deviation of the averages was significant at the highest level.

In conclusion, it can be stated that in the small-plot experiment carried out in 2021 and 2022, the high-dose 11th treatment (Vinasse 500 L/ha and zinc complex 0.5 kg/ha) had a positive effect on the yield of winter wheat. A closer correlation was obtained for the yield quality indicators since the significance level was P=1 % for the crude protein content and P=0.1 % for the wet fat content. The results can contribute to making agricultural production more sustainable and circular.

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# AI AND FRAUD PREVENTION: BIBLIOMETRIC ANALYSIS AND KEYWORD MAPPING IN THE CONTEXT OF SUSTAINABILITY

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The exponential growth of the digital economy is creating new opportunities and challenges for corporate security, particularly in the area of fraud. Not only can fraud cause significant financial losses, but it can also have a negative impact on consumer confidence and corporate image, making effective protection key to corporate sustainability. Artificial intelligence (AI) systems, particularly Machine Learning (ML) technologies, offer a promising solution to mitigate offline and online fraud, enabling companies to anticipate and mitigate such risks. The paper builds on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model to provide an overview of the use of AI technologies in the mitigation of fraud. The study aims to provide a comprehensive picture of how AI can reduce the success rate of fraud. The study also highlights how AI can help to promote corporate sustainability. In the literature review, studies from the selected scientific database were analysed, using inclusion and exclusion criteria to select those that provide relevant information on the role of AI technologies in identifying and addressing offline or online fraud. The results demonstrate that machine learning algorithms are particularly effective in detecting fraudulent activities by recognising patterns in large datasets. Furthermore, the study identified key trends and clusters in the scientific literature that show the growing role of AI and machine learning in fraud prevention, with a notable focus on the financial sector. Despite the benefits, challenges such as ethical concerns, misuse of AI, and the need for transparency in AI decision-making remain crucial. These findings highlight the necessity for companies to adopt AI strategically, balancing its potential and associated risks for a secure, sustainable digital economy.

## 1. Introduction

Fraud in business refers to an act whereby someone deliberately communicates false information or false statements to gain financial or other advantage, typically by causing harm to others (Bar Lev et al., 2022). Artificial intelligence (AI) has played an increasingly important role in the way companies operate in recent years, transforming traditional business models and improving efficiency in many areas (Writer, 2023). Nowadays, AI is a widely used technology in the corporate environment, playing a key role in decision-making, optimisation, customer experience improvement and risk management (Velikorossov et al., 2020). AI enables companies to proactively address challenges, respond faster to market changes and develop innovative solutions that give them a competitive advantage. Its impact on business operations is significant and is expected to grow in the future as the technology evolves and the scope of its applications expands (Tewari and Pant, 2020). Despite the many benefits that AI can bring to companies, there are also issues and challenges associated with its application, such as data privacy, ethical considerations and employee attitudes (Hirsch

et al.,2023). AI can also have an impact on the labour market, as the automation of certain tasks can reduce the number of jobs (Acemoğlu et al., 2022). In addition, the transparency and accountability of the decisions it makes can be a key issue in enterprise applications. Although AI can significantly reduce the error of fraud detection, it may also increase the success rate of fraud if not properly applied. Unethical use or poorly configured systems can provide an opportunity for fraudsters to circumvent the system. Therefore, companies need to carefully consider the benefits and risks of adoption and develop a strategy that maximises benefits while minimising risks (SKYbrary, 2023). Fraud in companies is increasing, representing a significant threat to companies. These irregularities can cause significant financial and non-financial damage, as well as damage to a company's reputation. Companies, therefore, need to monitor the various methods of misuse more closely and establish comprehensive policies and effective internal control systems to minimise the risks (Dewan PN Chopra & Co., 2023). This can be supported using artificial intelligence, machine learning and big data tools that can, for example, identify suspicious transaction patterns and take the necessary steps to prevent potential fraud (Lal et al., 2021). Of course, the continuous training of employees and managers and internal monitoring, as well as the involvement of external experts, are essential in the fight against fraud (Ann Riney, 2018). Recent studies highlight the increasing application of artificial intelligence (AI) and machine learning (ML) in the detection and prevention of fraud, yet there remains a lack of consensus in the literature regarding how these technologies are effectively integrated into corporate security frameworks. While many studies acknowledge the potential of AI and ML to enhance fraud detection, the specific relationship between these technologies and their practical application in fraud prevention is not consistently explored. Some studies emphasise the benefits of AI in detecting fraudulent activities, while others focus on the challenges of integrating machine learning algorithms into existing fraud detection systems. This paper seeks to address this gap by systematically analysing the existing literature to better understand how AI and machine learning are connected to fraud detection and to identify areas where further research is needed. The goal is to provide a comprehensive review of the state-of-the-art in AI-driven fraud detection, while also highlighting the knowledge gaps that remain in the field. The aim of this paper is also to verify the relevance of the literature selected for a systematic literature review, thus laying the groundwork for the meta-analysis. The central question of the study is: is the keyword variation generated by previous literature research suitable for a systematic literature search?

## 1.1. Fraud affecting businesses

Fraud against companies is often linked to embezzlement or unauthorised payments by internal staff, while fraud against consumers typically takes the form of overcharging, selling falsified products or false advertising. Combating fraud is key to maintaining economic stability and public confidence, which requires a thorough understanding of fraud schemes and the application of appropriate preventive and punitive measures (Whittaker, Button, 2020). But the threats to businesses today most often come in digital form. We are living in the age of online fraud. It should be mentioned that nowadays, money transfer scams are on a declining trend. Trading with fake products is a very common type of online scam. This type of scam is usually realized in social media or in online want-ad sites. Trust-based scams are rather a rare form of fraud. The phishing is one of the earliest forms of scams. In this case, scammers try to obtain information through messages to create false profiles from the obtained personal data. The lottery scam is another form of phishing where the damage is much more serious. The user receives an email from a supposedly genuine source, claiming that the user has won a lottery conducted by a particular organisation, and to claim the prize, the user needs to reply to the email immediately with the requested details. There is no lottery, and there is no prize waiting for the user. In the case of video scams or the process of video scamming, the user is involved and tricked into viewing an infected video containing malware (Gyurián Nagy, 2022).

## 1.2. Artificial intelligence and machine learning

Artificial intelligence can be a useful tool in fraud prevention. Machine learning algorithms can quickly and accurately identify suspicious transactions or activities so that companies can better protect themselves from losses and reputational damage (Horn et al., 2015). The use of AI can be useful not only in making a company's internal operations more efficient but also in managing external risks. Addressing external risks is a key issue for companies as threats are becoming more diverse and complex due to globalisation and digitalisation (VanSnick and Ntanos, 2018). Machine learning is an area of artificial intelligence that allows computers to solve tasks through learning without being explicitly programmed to do so. Machine learning

can recognise patterns in data, draw conclusions from them, and make reliable predictions for the future. This technology can be applied to a wide range of industries, from finance to agriculture, from transport to healthcare, enabling more efficient decision-making, process optimisation and cost savings (Jagatheesaperumal et al., 2021). It uses a variety of methods, such as supervised learning, reinforcement learning and self-organised or unsupervised learning. This allows systems to become increasingly adaptable to input data and changing environments, continuously improving performance (Richard, 2024). It also plays a key role in the development of artificial intelligence, enabling computer systems to perform tasks that they were previously unable to do. As technology advances, machine learning will have an increasing impact on all aspects of life, changing the way humans work, entertain and even provide healthcare (Mallik and Gangopadhyay, 2023).

## 2. Methodology

The aim of the study is to prepare a systematic literature analysis using the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). PRISMA method is an internationally recognised guideline aimed at improving the transparency and completeness of systematic reviews and meta-analyses (Moher, 2009). The paper will outline the topic and justify its relevance and importance. Subsequently, the basic principles of the PRISMA method are explained, and its practical application in the field is described. The method is used in this study to describe the inclusion and exclusion criteria and the various characteristics and links of the studies filtered by it. The keywords used for the literature search were ("Artificial intelligence" OR "AI" OR "Machine learning") AND ("Fraud detection" OR "Corporate security"), which resulted in a total of 1279 articles. Of these, 97 articles are related to the business and economics research area. The total number of articles published in the period 2020-2024 is 85. The reason for this period is the number of fraud cases, which has been on a significant increase since 2020. Among these references, 58 are classified as scientific articles. After excluding the non-English language, 56 articles remain to be included in the analysis. The methodological steps are illustrated in Figure 1.

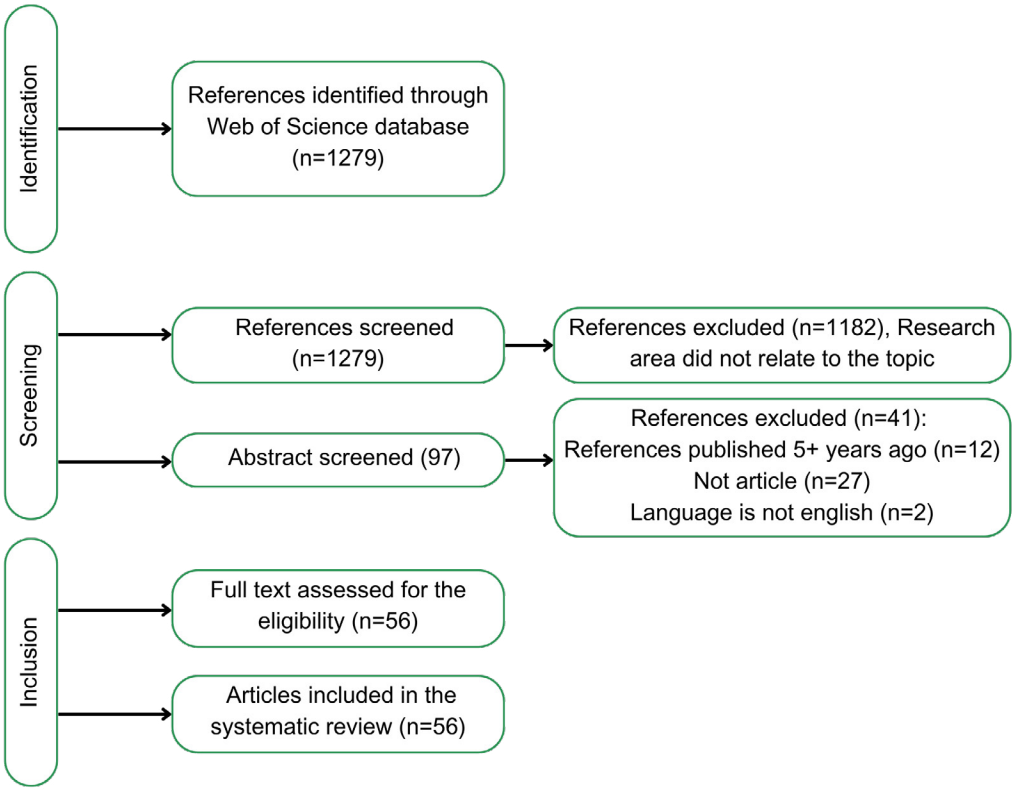


*Figure 1: Systematic literature review using the PRISMA method*

# 3. Results and discussion

Sustainability is a high priority today. The analysis cannot neglect the presence of sustainability in the studies. Figure 2 illustrates which of the SDGs are the most emphasised by the authors. The dominance of the goal "Good Health and Well Being" shows that health and improving well-being are key issues in the research. This probably reflects the importance of health challenges and health systems development. The appearance of 'Quality Education' and 'Sustainable Cities and Communities' indicates that quality education and sustainable development are also important areas. The moderate role of 'Decent Work and Economic Growth' and 'Industry Innovation and Infrastructure' indicates that economic growth and innovation are also important but not dominant themes. Poverty and inequality reduction is less prominent in the studies.

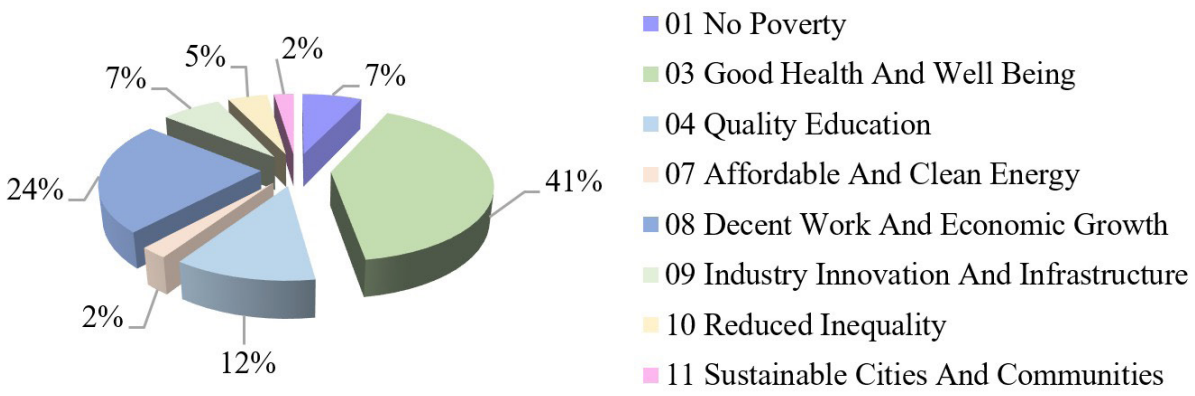


*Figure 2: SDGs in the studies reviewed*

## 3.1. Scientific context mapping with VOSviewer

VOSviewer analysis was used to explore the relevance of the relationships and the relevance of the keywords. The analysis has drawn clusters, which are presented in Table 1.

*Table 1: Clusters drawn by the VOSviewer analysis*

| Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 |
|---|---|---|---|---|
| Data mining | Automobile insurance | Artificial-intelligence | Artificial intelligence | Corporate fraud |
| Financial statement fraud | Claims | Blockchain | Big data | Fraud |
| Machine learning | Deep learning | Data Analytics | Classification | Governance |
| Management fraud | Fraud detection | Impact | Finance | |
| Model | System | Opportunities | | |
| Regression | | | | |

*Figure 3 illustrates a density map showing the frequency relationships between keywords in the topic examined. The density map can be used to identify which keywords occur more frequently together in the publications examined.*

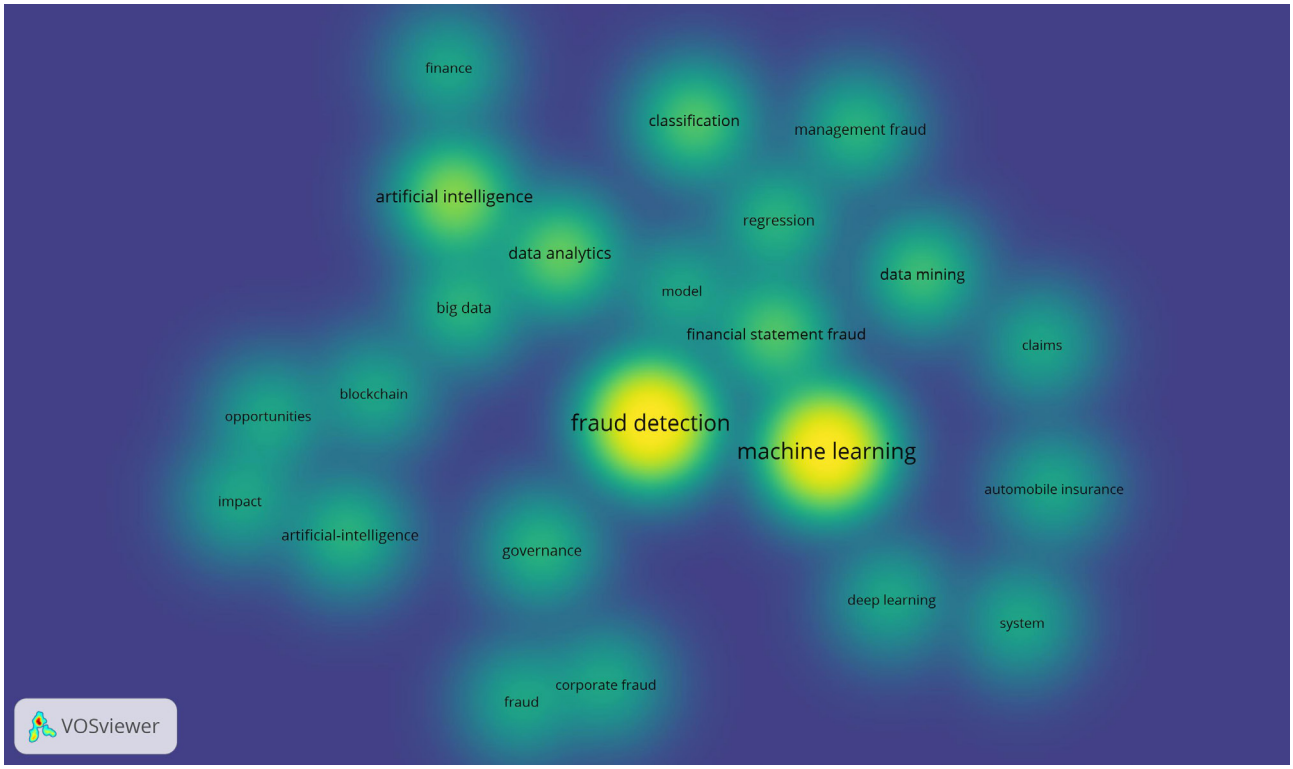


*Figure 3: Density map of keywords used in the studies included in the VOSviewer analysis*

The keywords “fraud detection” and “machine learning” have the most intensive spots, indicating that they are the most frequently occurring and most important topics. Around these there are several other keywords, all related to these two main topics, indicating a tight network of connections. The keyword “artificial intelligence” also has a significant density, indicating that artificial intelligence is also frequently included in the fraud detection topic. The density map shows that this keyword is also related to several other concepts, such as “big data” and “data analytics”. The keywords “data analytics” and “big data” also have a relatively high density, indicating that data-driven approaches are key to fraud detection. This confirms the trend that big data analysis and management are fundamental to modern fraud detection methods. The keywords “blockchain” and “governance” also appear in the figure, with less intensity. This suggests that these technologies and concepts are relevant but perhaps less central. “Blockchain” may be of particular interest for future research as it offers new opportunities to increase transparency and data security in fraud detection. The keywords “financial statement fraud” and “corporate fraud” are also included in the figure, indicating that fraud detection is also focusing on different types of fraud. These keywords have a lower intensity but are important for the detection of specific areas of research.

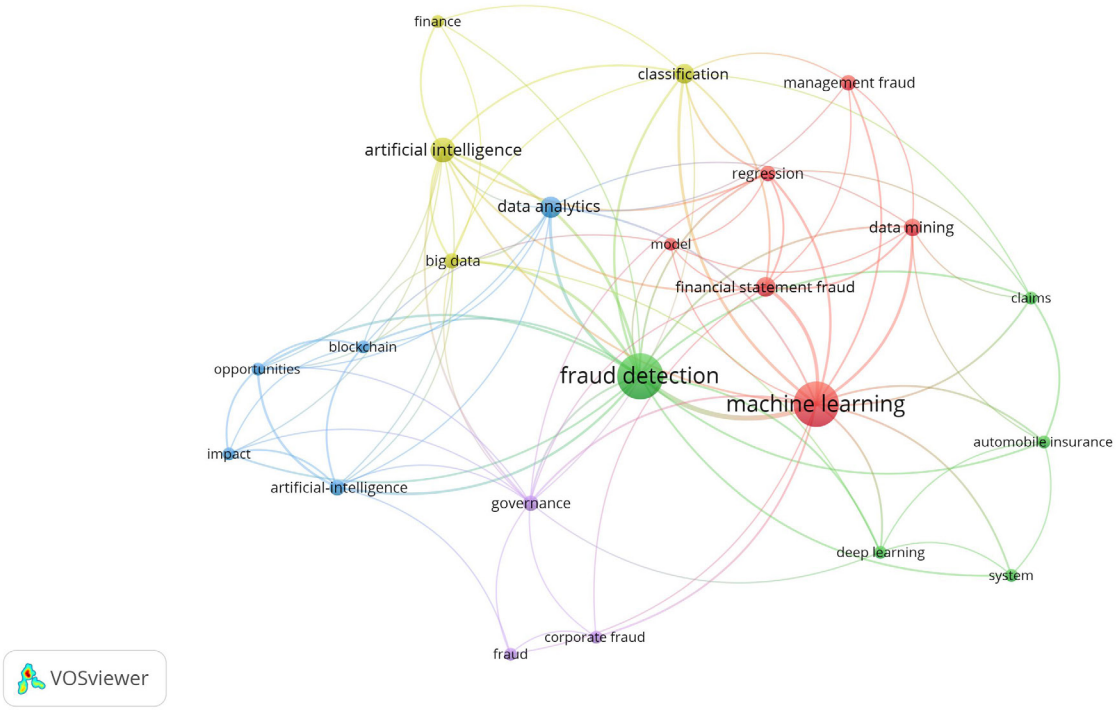


*Figure 4: Relationship map of the keywords included in the VOSviewer analysis*

Figure 4 is a relationship analysis diagram showing the relationships between different keywords in the topic under study after screening with the PRISMA method. The analysis was performed using VOSviewer software, a software for visualising the relationships between scientific publications. The aim of the analysis is to provide a visual representation of the topics and keywords related to fraud detection and how they are interrelated. It allows easy and clear identification of important areas and research directions in this field. The graph uses different colours and thicknesses of lines to show which keywords are related and how strongly they are related. The graph shows that there are three major clusters in the topic under study to which the other keywords are linked. These three main components are fraud detection, machine learning and artificial intelligence. The thickness and colour of the lines indicate the strength of the relationship between the keywords. Obviously, thicker lines indicate a stronger connection, and thinner lines indicate a weaker connection. Clusters of nodes with the same colour are more frequently related, such as "machine learning" and "data mining" are coloured red, indicating that they occur frequently together. Based on the analysis, the strongest fraud detection keywords are associated with the keywords financial statement fraud, management fraud, corporate fraud and governance. The machine learning keyword is closely related to the keywords data mining, classification, regression, deep learning and model. The keyword artificial intelligence is mainly related to the keywords big data, data analytics and finance. The analysis shows that fraud detection is the central component, and several other keywords are related to it. This indicates that fraud detection is central to the research area, i.e. the choice of search criteria was appropriate. Machine learning is also central and strongly related to fraud detection. This suggests that machine learning could be a key method in fraud detection. The third main keyword, "artificial intelligence", is also a significant node, suggesting that AI has a wide range of applications in fraud detection. It has emerged that AI and machine learning are closely linked to fraud detection, particularly in the financial sector. The dominant presence of the financial sector is also reflected in the presence of more obscure keywords: "blockchain" and "governance" are also important topics; these new technologies and methods, such as blockchain, offer opportunities for fraud detection and prevention. Financial statement fraud" and "corporate fraud" refer to specific types of fraud, which are also related to the main areas.

# 4. Conclusions

The use of machine learning and artificial intelligence in fraud detection is growing. These tools can analyse large amounts of data and recognise patterns that are critical to fraud detection. The close association of the keywords "big data" and "data analytics" shows that data-driven approaches are also crucial. Blockchain technology, although less central, could potentially play a significant role in future fraud detection methods. By increasing data security and transparency, blockchain can help to prevent and detect fraud. Financial fraud, such as statement fraud and corporate fraud, is a priority. This indicates that these forms of fraud are a priority problem and require targeted research. Research into financial reporting fraud and corporate fraud remains relevant as these forms of fraud can cause significant economic damage. Research focusing on these areas can help to develop more effective detection and prevention strategies. Insurance fraud is another important area where the use of machine learning models and artificial intelligence is of growing importance. The diversity of the graphs produced by the VOSviewer analysis suggests that fraud detection research requires an interdisciplinary approach. Collaboration between different fields, such as finance, IT and AI, is key to developing effective fraud detection strategies. The analysis has shown that the keywords selected based on previous literature monitoring are suitable for a systematic literature review. The study showed that the PRISMA method is relevant in its current form. For future analyses, it would be useful to explore fraud in the financial sector within the subject area. As a continuation of the research, the aim is to identify the main topics based on the 56 selected studies and to proceed to a meta-analysis.

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# ANALYSIS OF HERBICIDE EFFICACY IN DETERMINING THE LIMITATIONS OF TRADITIONAL SORGHUM WEED CONTROL AND EXPLORING FUTURE OPPORTUNITIES

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**The excessive use of pesticides raises environmental concerns. New technologies, like imidazolinone-, nicosulfuron-, and quizalofop-P-ethyl-tolerant sorghum hybrids, offer improved weed control. These innovations promote sustainability by reducing chemical dependence. Evaluating past plant protection strategies is essential for refining future approaches. Dicamba is more effective than clopyralid for dicotyledonous weed control. However, dicamba has limited effectiveness against Cirsium arvense. Soil-acting herbicides like Gardoprim® Plus Gold mainly target monocots but lack post-emergence control. The best herbicide effect was achieved with pre-emergence and post-emergence technology applied in time. The effectiveness was 90-99 % for monocotyledons and 96-99 % for the main dicotyledonous weeds. Late application timing significantly reduces efficacy, as seen with Panicum miliaceum and Echinochloa crus-galli. This leads to increased weed competition and reduced sorghum yields. The withdrawal of S-metolachlor highlights the need for new monocot herbicides. Herbicide-tolerant sorghum hybrids could address this issue. Further research is crucial to optimize these technologies. These solutions must be integrated into sustainable farming practices. New herbicide-tolerant varieties can help sorghum thrive despite weed pressure. Continued investment in research is essential for sustainable crop production. Integrating effective herbicides reduces the environmental impact of farming.**

## 1. Introduction

Sorghum (Sorghum bicolor) is a drought-resistant crop requiring fewer pesticides and irrigation, reducing environmental damage from fuel use. Efficient herbicide applications tailored for drought-resistant crops like sorghum promote sustainable food production while minimizing resource consumption and environmental harm. Weeds significantly affect sorghum yields, causing 34 % of yield losses (Jabran et al., 2015). Sorghum is a weak competitor against weeds due to its slow growth. Herbicide options are limited due to few registered products and European regulations like the ban on S-metalachlor starting July 2024 (Alvarez et al., 2023). Protection of sorghum is also limited by the low number of registered herbicides (Correia and Gomes, 2015). The overuse of herbicides with the same mode of action can lead to resistant weed biotypes (Bhowmik and Inderjit, 2003). There's a research gap on sorghum weed control in Hungary, making it difficult to assess herbicide effectiveness. This study aims to analyze herbicide effectiveness at different application times, helping identify future opportunities and selective herbicide solutions for sorghum.

## 2. Situation of sorghum weed control

Fewer control options are present in the control of sorghum weeds than in corn (Grichar, 2006). The plant is less tolerant of the most used monocotyledonous and dicotyledonous herbicides. Furthermore, deeper than

optimal sowing, unfavorable soil physical conditions and low seed germination quality can also contribute to the stress of young plants, which can make the plant particularly sensitive to the herbicides used (Peerzada et al. 2017). The presence of herbicide-resistant weeds, the restriction of crop rotation, and the lack of a limited number of available registered herbicides represent a significant challenge in sorghum weed control (Fromme et al., 2012). Members of the *Poaceae* family, especially weed species of the genera *Echinochloa* spp., Panicum spp., *Digitaria* spp. and *Sorghum halepense* in the southern United States, such as grain sorghum, are widespread and problematic (Hoste and Verloove, 2022). According to Novák et al. (2020), based on the sixth nationwide field weed survey conducted in 2018-2019, the ten most problematic weeds in Hungary include *Ambrosia artemisiifolia L.*, *Chenopodium album L.P.B.*, *Echinochloa crus-galli (L.)*, *Sorghum halepense(L.) Pers.*, *Setaria pumila (Poir.) R. et Sch.*, *Convolvulus arvensis L.*, *Datura stramonium L.*, *Amaranthus retroflexus L.*, and *Cirsium arvense (L.) Scop.*

## 2.1. Weed Control with Synthetic Products

By combining biotechnological methods and traditional breeding, several cultivated plants have already been created that are resistant to widespread weeds and various environmental challenges. These plant varieties do not contain a gene from a foreign organism, so they cannot be considered transgenic but can rather be classified as non-transgenic herbicide-resistant plants. The most significant technology in this area is based on imidazolinone resistance, also known as Clearfield technology, which utilizes the effect of imidazolinones to enable a wide range of control against monocotyledonous and dicotyledonous weeds while remaining ineffective against legumes plants. The breeding of herbicide-resistant sorghum expands weed control options, though its use is not yet permitted in Hungary. igrowth®, developed by Advanta Seeds, is the first commercially available imazamox-resistant sorghum, introduced in Argentina and Australia in 2020. Imazamox, an imidazolinone herbicide, is used post-emergence in crops like alfalfa, legumes, and soybeans. It inhibits acetolactate synthase (ALS), an enzyme essential for amino acid synthesis in plants, leading to growth cessation and eventual plant death over several weeks. The first resistant sorghum hybrid was registered under the name Sentinel IG. Using ImiflexTM (12.1% Imazamox) in Argentina, and Intervix® (33 g/L Imazamox + 15 g/L Imazapyr) in Australia, the non-GMO technology allows the control of dicotyledon and monocotyledon weeds without causing loss of crop yield. Due to the active ingredient imazamox, Imiflex™ and Intervix® are Group 2 herbicides that belong to the imidazolinone (IMI) family. Based on the results of previous research, this group of compounds provides effective protection against yield-reducing weeds, especially in the 2-6 leaf stage of cultivated plants, especially when applied post-emergent, but also in the case of pre-emergent application (Currie et al., 2023). In Hungary, preparations containing imazamox can be used, the active ingredient giving outstanding effectiveness against *Datura stramonium*, *Chenopodium hybridum*, *Amaranthus spp.*, *Solanum nigrum*, *Brassica spp.*, *Raphanus raphanistrum* species. Imazamox is slightly persistent, which means that it breaks down in the environment in a short time, thus minimizing harmful effects on the environment. This contributes to the continued presence of imazamox on the European market, while other imidazolinone-type substances with similar effect were previously withdrawn from the market. This makes imazamox an outstanding choice for effective weed control and environmental protection (Aichele and Prenner, 2005). However, imazamox belongs to the group of herbicides with the ALS mode of action, to which resistance has already been demonstrated in several weed species. The emergence of resistance to ALS-inhibiting herbicides means that igrowth® technology must be combined with other effective herbicide modes of action to suppress resistant plants and slow the development of further herbicide resistance (Brunharo, 2022). In 2021, in the United States (US), Corteva Agriscience™ will also introduce Inzen™ grain sorghum hybrids that are resistant to the post-emergent monocot nicosulfuron. The trade name of the herbicide associated with the Inzen™ technology is Zest™ WDG (75% nicosulfuron). Post-emergent application of herbicide can be carried out from 10.16-50.80 cm (4 and 20 inches), that is, from the 5-leaf stage, until the appearance of the flag leaf (Bowman et al., 2020). Nicosulfuron is effective post-emergence against hard-to-eradicate weeds in corn and soybean (Mekki et al., 1994). It can complement or replace pre-emergent treatments, especially in high-organic soils. It controls annual monocots like *Panicum dichotomiflorum* and *Echinochloa crus-galli*, as well as many perennial monocots and dicotyledonous weeds, including *Chenopodium album*, *Ambrosia artemisiifolia*, *Abutilon theophrasti*, *Xanthium strumarium*, and *Solanum ptycanthum* (Rahman et al., 2003). When InzenTM is allowed to expand the ALS mechanism of action, there are more opportunities to diversify herbicides. Werle et al. (2016) confirmed cross-resistance to nicosulfuron and imazethapyr in *Sorghum halepense* populations in Kansas, Missouri, and Nebraska. The spread of ALS-resistant *Sorghum halepense* highlights the need for careful use of Inzen™ technology (Bowman et al., 2020). Double

Team, the third post-emergent quizalofop-P-ethyl weed control system after Corteva Inzen™ and Advanta igrowth®, was developed by S&W Seed Company and ADAMA Ltd. and approved by the U.S. EPA in 2021. Quizalofop-P-ethyl, a group 1 HRAC "A" herbicide, inhibits the ACC-ase enzyme, disrupting fatty acid biosynthesis and leading to plant death (Rendina and Felts, 1988). Graminicides, which target Poaceae monocots, can be applied post-emergently against seed-emergent and perennial monocot weeds (Abdullahi et al., 2001; Gronwald, 1991).

# 3. Material and Method

In the experiment, 7 treatment mesoplots (3x50 m) were planted with sowing on 5 May 2023 at the teaching farm of the Szechenyi Istvan University in Mosonmagyaróvár. In the study, we examined the medium-early-mature RGT Huggo hybrid distributed in Hungary by RAGT Vetőmag Kft. with a row spacing of 75 cm and a sowing rate of 270,000 seeds/ha. The time and doses of the preparations used can be found in Table 1. During the experiment, the early postemergence sprays were on 19.05.2023, when the sorghum was still in the germination phase (BBCH 10). Early post-emergence treatments were carried out on 05.30 in the 4-leaf development stage of sorghum (BBCH 14).

In the experiment, we used an herbicide effect evaluation, for which we used the following EPPO guidelines (Kalamarakis and Markellou, 2007):

PP 1/50(4): Weeds in Maize

PP 1/152(3): Design and Analysis of Efficacy Evaluation Trials

PP 1/181(3): Conduct and Eporting of Efficacy Evaluation Trials Including GEP

PP 1/135(3): Phytotoxicity Assessment

PP 1/239(2): Dose Expression for Plant Protection Products

Dose expression for plant protection products was performed on June 7, one week after the second post-treatment. The second evaluation is on June 30, 1 month after the second post-treatment. The third evaluation took place shortly before harvest on September 28. Data were collected after one growing season of treatments. The data collected at this time included the percentage of weed coverage in each plot. For weed coverage sampling, three randomly placed 1-meter square quadrats were sampled in each plot. Herbicide effectiveness was rated on a scale of 0 to 100, where 0 indicates no effectiveness, and 100 indicates perfect weed control. A visual assessment of weed control was conducted based on the average of the three sample plots compared to the untreated control plot. The relationship between weed coverage and herbicide effectiveness is assessed by comparing the piece of weed coverage in treated plots to that in untreated control plots. As the weed coverage in a treated plot decreases, the herbicide effectiveness score increases, indicating more effective weed control. Herbicide effectiveness is inversely related to weed coverage. Greater reduction in weed coverage leads to a higher effectiveness score, while less reduction results in a lower score. If weed coverage in treated plots is lower than in the control, the herbicide is more effective. During the spraying, the spraying was carried out at a pressure of 3 bar and a speed of 4.5 km/h, with a spray amount of 260 liters/hectare and with a Lechler ID blue flat radius (110°) nozzle. Banvel 480 S was used in the lower dose allowed of 0.5 l/ha, while Gardoprim® Plus Gold was used according to the license document at 4 L/ha. For Cliophar 600 SL, it was used a higher dose of 0.3 L/ha, compared to the 0.2 L/ha recommended for corn. In this way, the effectiveness of different treatment strategies was thoroughly analyzed to discover new approaches and opportunities to optimize the effect of the active ingredients.

# 4. Results

During the recordings, a total of 17 different species of weeds were recorded. Special attention was paid to six of these species, against which we tested the effectiveness of the pesticide shown in Table 1. Based on early summer and autumn surveys, the top two positions are occupied by *Cirsium arvense* and *Ambrosia artemisiifolia* fields. Over the past 71 years, *Cirsium arvense* has consistently ranked among the ten most common weeds in the six most recent national field weed surveys. On the other hand, we witnessed the aggressive advance of *Ambrosia Artemisiifolia*. From 21st place in the survey between 1947-53 to eighth place in almost 20 years, and after 10 years, it is still in first place on the list of importance. According to our current survey, it is still in first place, with an average number of 31 pieces /m$^2$, which is 5.5 % higher than *Cirsium arvense*. During the survey, the *Chenopodium album*, which was present in the surveyed 8 pieces/m$^2$, received considerable attention. This plant has consistently ranked second and third in the last six field surveys. It is also important to mention the situation of *Panicum Miliaceum*, as it is a problem in almost every treatment. Examining the preharvest condition, *Panicum Miliaceum* is one of the most important monocot weeds in our survey since we found 12 plants per square meter. Considering the pre-harvest conditions, we can conclude that almost all the untreated control stands were under severe weed pressure. The post-emergence application of Banvel 480 S at emergence resulted in a lower-than-average level of weed control efficiency, as the preparation is completely ineffective against monocotyledonous weeds. Among the dicotyledonous weeds recorded in the largest number, *Ambrosia Artemisiifolia* achieved an excellent 98 % efficiency, while *Cirsium Arvense* achieved a weaker 81 % efficiency.

*Table 1: Effectiveness of selected herbicides in mono- and dicotyledonous weed*

| Treatment | Time of application BBCH | Dose | Weed Control | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | AMBEL | PANMI | CIRAR | CHEAL | ECHCG | CHEHY | Others |
| Control | - | - | *31/m$^2$ | *12/m$^2$ | *20/m$^2$ | *8/m$^2$ | *7/m$^2$ | *4/m$^2$ | *17/m$^2$ |
| | | | Herbicide effectiveness in percentage (%) | | | | | | |
| Banvel 480 S (480 g/L dicamba) | 10 | 0.5 L/ha | 98 % | 0 % | 81 % | 95 % | 0 % | 90 % | 96 % |
| Cliophar 600 SL (600 g/L clopyralid) | 10 | 0.3 L/ha | 98 % | 0 % | 90 % | 0 % | 0 % | 0 % | 91 % |
| Gardoprim® Plus Gold (312 g/L S-metolachlor + 187 g/L terbuthylazin) + Banvel 480 S (480 g/L dicamba) | 10+14 | 4 L/ha + 0.5 L/ha | 98 % | 90 % | 96 % | 99 % | 99 % | 99 % | 100 % |
| Cliophar 600 SL (600 g/L clopyralid) | 14 | 0.3 L/ha | 98 % | 0 % | 96 % | 0 % | 0 % | 0 % | 90 % |
| Gardoprim® Plus Gold (312 g/L S-metolachlor + 187 g/L terbuthylazin) + Banvel 480 S (480 g/L dicamba) | 14 | 4 L/ha + 0.5 L/ha | 91 % | 0 % | 96 % | 99 % | 60 % | 99 % | 96 % |
| Gardoprim® Plus Gold (312 g/L S-metolachlor + 187 g/L terbuthylazin) | 14 | 4 L/ha | 87 % | 0 % | 65 % | 99 % | 60 % | 99 % | 95 % |

**Number of weeds per m$^2$*

*AMBEL, Ambrosia Artemisiifolia, PANMI, Panicum Miliaceum, CIRAR, Cirsium Arvense, CHEAL, Chenopodium Album, ECHCG, Echinochloa Crus-Galli, CHEHY, Chenopodium Hybridum*

The postemergence application of Cliophar 600 SL at the time of emergence showed a much stronger efficiency against those with nested inflorescences, but at the same time, it performed less well against Chenopodium species. Dicamba demonstrated 95 % efficacy in controlling Chenopodium album, whereas clopyralid showed no effectiveness. For Chenopodium hybridum, dicamba again exhibited a high efficacy of 90 %, while clopyralid failed to prevent the weed's spread. As a result of the early implementation of weed control, the active ingredient was unable to suppress late-emerging Chenopodium species with satisfactory efficiency. Due to its mechanism of action against only dicotyledons, the herbicide did not show any effectiveness against monocotyledonous weeds. After Gardoprim® Plus Gold application at emergence, the post-emergence herbicide Banvel 480 S was used when the sorghum plants had already reached the 4-leaf stage. The application of the two different herbicides at different times reached a wider spectrum of weeds, and their combined effect proved to be more powerful. The lack of an outstanding weed-killer effect can be partly attributed to the fact that in the two weeks after the very early postemergence treatment, the wash-in rainfall was only 9.4 mm, which was below the required 15-20 mm, so the effectiveness of the active ingredients through the soil was not perfect either. The active ingredient dicamba applied post-emergent effectively (96-100 %) killed the remaining dubious weeds that survived the very early post-emergence treatment due to the deficiencies of the wash-in precipitation. Compared to other weed species, only Panicum miliaceum had a weaker 90 % weed-killing effect. During the sixth treatment, Gardoprim® Plus Gold+Banvel 480 S treatments were applied post-emergently at the 4-leaf development stage (BBCH 14) of sorghum. The effectiveness of this treatment was moderate, which is partly since the active substances acting through the soil did not achieve their expected effect due to the very early postemergence application. Although 63.9 mm of rain fell in the two weeks after treatment, which could potentially have helped inhibit soil germination, it no longer affected weed emergence. Under suboptimal conditions, the efficacy of pre-emergence control decreased substantially, dropping from 90 % to 0 % for Panicum miliaceum and from 99 % to 60 % for Echinochloa crus-galli because of delayed application. Dicamba was the only active ingredient that worked effectively through the leaf against dicotyledonous weeds. During the seventh treatment, only Gardoprim® Plus Gold was used after emergence, when the sorghum plants were also in the 4-leaf development stage. This treatment showed an even weaker effect, as it lacks the active ingredient dicamba, which would have worked through the leaves. It is interesting to note that the Gardoprim® Plus Gold preparation, although it allows preemergence and early postemergence use, did not cause phytotoxic symptoms even after the 4-leaf development of sorghum. Compared to treatment four, where the preparation was used during the germination period, it can be observed that its effectiveness against monocotyledonous and dicotyledonous weeds was lower in the case of later use.

# 5. Conclusions

Based on the comparison of the effects of dicamba and clopyralid, it can be concluded that dicamba is more relevant in weed control due to its wider spectrum of action. Dicamba demonstrated 95 % efficacy in controlling *Chenopodium album,* while clopyralid showed no efficacy. For *Chenopodium hybridum*, dicamba was also highly effective, with a 90 % success rate, while clopyralid once again failed to control the weed's spread. The active ingredient dicamba demonstrated a relatively low efficiency of 81 % against *Cirsium arvense* in our study, representing the weakest performance among the tested broadleaf weed control agents. This suggests an opportunity to enhance its effectiveness through further optimization or integrated application strategies. In the study, a significant challenge in sorghum production is the lack of effective post-emergence control for monocotyledonous weeds. Under suboptimal conditions, the efficacy of pre-emergence control decreased significantly, dropping from 90 % to 0 % for *Panicum miliaceum* and from 99 % to 60 % for *Echinochloa crus-galli* due to delays in application. When the mechanism of action of Gardoprim® Plus Gold and similar agents is examined, it can be concluded that the effect against monocot species is generally based on absorption through the soil, while the effect on leaves is limited. Consequently, an increase in monocot weeds was observed in the postemergence treatment, while the very early postemergence treatments, i.e., the treatment that preceded it in the treatment of the monocot species, did not have this type of problem. Herbicide-tolerant technologies such as imidazolinone-tolerant sorghum (IMI sorghum) and nicosulfuron-tolerant sorghum (SU sorghum) offer new opportunities for weed control and do not require rainfall for activation, which enhances their flexibility in application. IMI sorghum broadens the effect against monocotyledons and dicotyledons. The active ingredient imazamox can be used against species such as *Setaria spp*., *Chenopodium album*, *Solanum spp*., *Amaranthus retroflexus*, and *Digitaria sanguinalis*. These are

also the results of treatment in imidazolinone-tolerant maize that are supported. The post-emergence use of nicosulfuron-resistant sorghum effectively combats monocots, including perennials and seeded species. However, in the case of *Sorghum halepense*, resistance monitoring is important. Sorghum that is tolerant to quizalofop-P-ethyl, which belongs to the ACC-ase group of active ingredients, offers new possibilities in weed control. With post-emergence treatments, the effect against monocots can be broadened, including protection against *Sorghum halepense*. However, it is important to monitor the development of resistance, as it can be a widespread problem in sorghum and other monocots, such as *Sorghum halepense* and *Setaria viridis*. Several literary sources support the effectiveness of ACC-ase inhibitors, and there can be a parallel with the DUO system technology already used in corn, where an excellent weed-killing effect can be achieved by using cycloxidim in corn tolerant to the active ingredient cycloxidim, *Sorghum halepense, Elymus repens*, *Cynodon dactylon*, *Setaria spp*., against *Echinochloa crus-galli*.

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# IMPLEMENTATION OF AUTOMATED CONTROL ON TEST VEHICLE FOR SAFE MOTION IN ROUNDABOUTS

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**This paper presents an innovative solution for testing automated vehicle (AV) control systems in real roundabout scenarios. The main difficulty of testing solutions is that they require safety manoeuvres with multiple vehicles, which is costly and time-consuming. The application of Augmented Reality (AR) can provide a solution to this problem, as a large number of virtual vehicles can be easily simulated and visualised without the need for further physical test vehicles. The aim of this paper is to present the test environment using the example of a hierarchical control strategy.**

## 1. Introduction and motivation

The design of control for a safe and time-efficient motion of AVs in roundabout scenarios presents several challenges, particularly in adapting to the actual traffic scenario and coordinating the vehicles. Collision avoidance between participants, whether a human-driven vehicle or an autonomous vehicle, of the traffic situation stands in the center of proposed control strategies aiming the safe crossing of roundabouts. The most important three open problems based on the survey of Campi et al. (2024) are as follows: (1) traffic management in roundabouts with AVs poses the problem of vehicle ordering and motion profile design; (2) the development of accurate driver models, the assessment of AVs' behavior and driving comfort, and the exploration of advanced learning schemes and cooperative decision-making algorithms are crucial for addressing these challenges. (3) Additionally, the use of dynamic driving simulators and empirical studies can provide valuable insights into the behavior of AVs, connected AVs or Cooperative, Connected AVs in roundabouts. Masi et al. (2020) propose a control strategy to ensure collision-free navigation through one- and two-lane roundabouts by autonomous vehicles while adhering to priority constraints. Azimi et al. (2014) have developed a vehicle-to-vehicle communication and control method for autonomous vehicles to ensure safety in complex traffic scenarios, such as roundabouts. Wang et al. (2012) have designed a control algorithm that estimates vehicle states for trajectory tracking, addressing the challenge of collision avoidance in roundabouts. The interactions between vehicles are modeled using a game-theoretic approach, which is employed in the decision-making algorithm. Debada et al. (2016) have proposed a distributed control method comprising reactive and predictive strategies for determining priorities, aimed at coordinating autonomous vehicles as they navigate roundabouts.

In spite of the high number of theoretical results, there are only a few papers that deal with the verification of the designed algorithms based on real-vehicle implementations on roundabout scenarios. Wang et al. (2022) have proposed an interaction-aware safety evaluation framework for the AVs, with which a high number of scenarios can be generated for control evaluation purposes. Németh and Gáspár (2023) also provide a testing method for vehicle control in general interactions, but it is limited to small-scale test vehicles. Vinayak et al. (2023) also demonstrate an implementation but that focuses on the lateral control system. Thus, it shows that there is a gap between the applied testing solutions and the theoretically achieved results, i.e., the results must be verified under real test scenarios.

This paper presents the implementation of a hierarchical motion control strategy with learning functionality for roundabout scenarios. The control is designed with two levels: one with a learning-based agent and one with a model-based control. The learning-based agent is created using reinforcement learning, while the model-based control is designed using robust PID control techniques. These two levels are coordinated through a supervisor in order that collision avoidance is ensured. The study demonstrates the effectiveness of the method through implementing it on test vehicle Nissan Leaf, that is the main novelty of the paper, because the presented control strategy has not been tested under real vehicle yet. The test scenario is realized together with the parallel running of virtual vehicles, i.e., the test vehicle has to adapt to surrounding vehicles. The provided scenarios illustrate that the automated vehicle can move safely without collisions and similarly, the time-efficient motion can be achieved.

## 2. Architecture of the hierarchical control strategy

The fundamentals of the hierarchical control strategy can be found in Németh and Gáspár (2023). The aim of the control strategy is that a model-based control and a learning-based control work together under a supervisor. The learning-based control is able to provide high-performance motion due to the reinforcement-lerarning-based (RL) training process, although the stability of the algorithm cannot be achieved. Stability and avoiding performance loss are guaranteed by the model-based control, but that leads to low performance due to its simple structure. The aim of the supervisor is to combine the outputs of the two controls. It means that the candidate signal of the learning-based control $u_L$ is preferred is stability can be preserved with $u_L$. But, if stability or performance loss are resulted by $u_L$, then the control signal is limited by the robust domain around the output of the model-based control $u_K$. The final control input of the system is he output of the supervisor, that is formed as , where  is the result of the quadratic optimization within the supervisor. The control strategy together with its formulas are detailed in Németh and Gáspár (2023).

The illustration of the control system implementation on an algorithmic level can be shown in Figure 1. The "ROS data in" and "ROS data out" blocks represent the communication between the Matlab model and the Nissan Leaf test vehicle. The Simulink model's input is the Leaf's actual position, and its output is the required steering angle and velocity. The other output is the environment vehicle's position and yaw values, which are sent to a smartphone through a TCP/IP protocol. The phone is attached to the windshield of the test vehicle, and it is running a Unity app in order to display other vehicles on the picture of its camera in real-time. Although the paper deals with speed profile design, a comment is added to the lateral control. The desired steering angle is calculated with a PID controller, whose input is the lateral error of the test vehicle, calculated based on the predicted position, calculated with the use of the yaw angle.

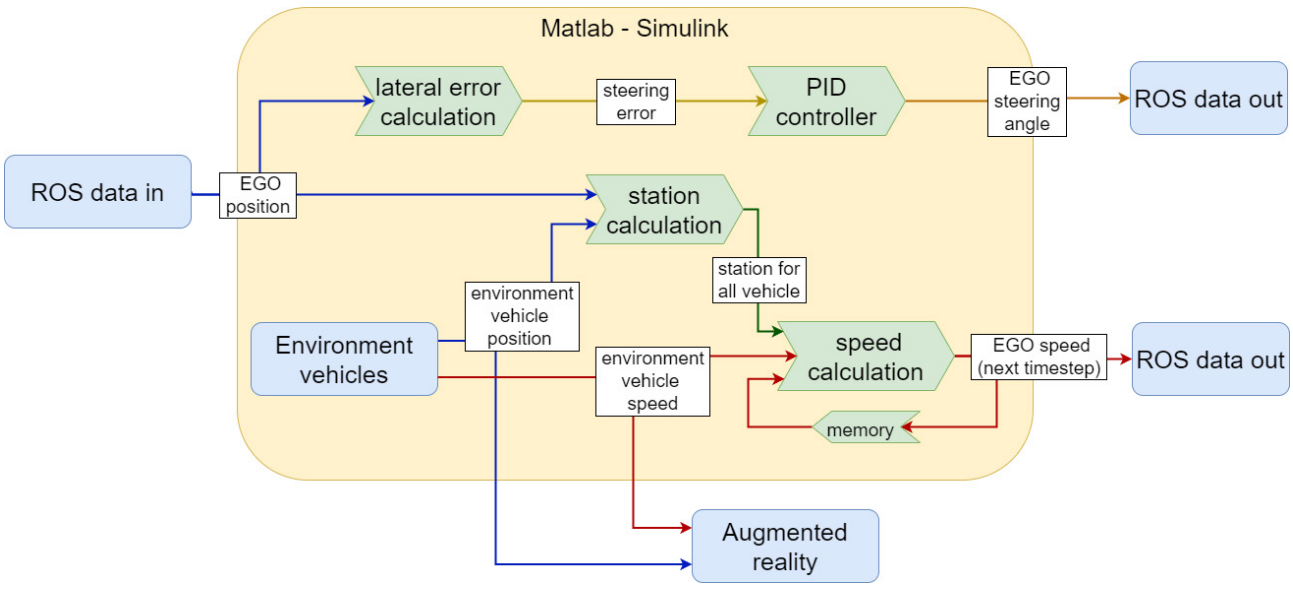


*Figure 1: The working principle of the system*

Figure 2 shows the scheme of the speed calculation algorithm. The block "optimization" contains the quadratic optimization of the supervisor, i.e., the value of Δ is calculated based on the vehicles' station and velocity, on the $u_K$ and $u_L$ acceleration values. The EGO data calculation algorithm is determining the main output, based on the Δ acceleration and the EGO vehicles's velocity from the previous time-step.

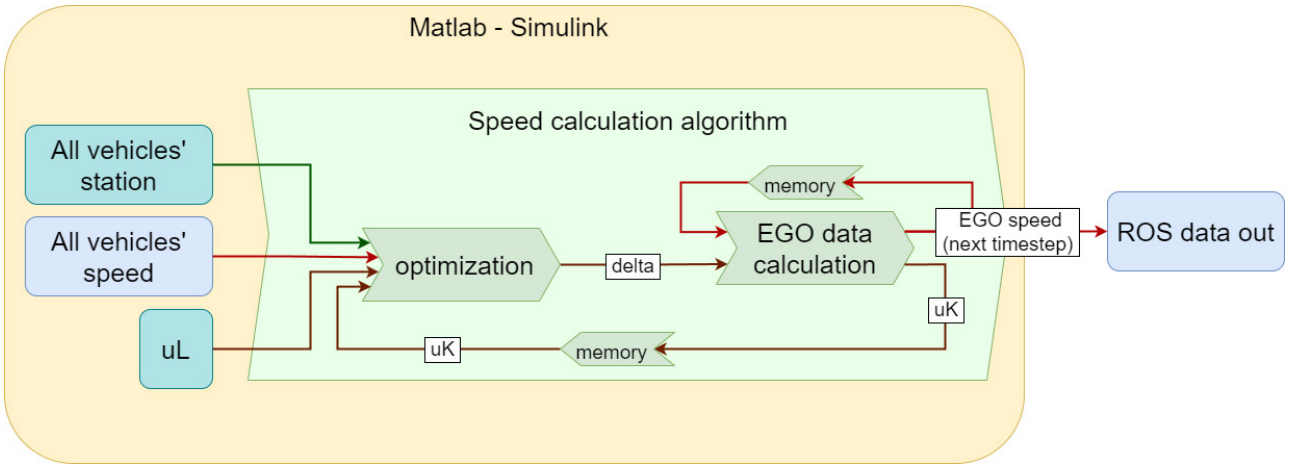


*Figure 2: Speed calculation algorithm*

The candidate acceleration command $u_L$ is the output of the RL agent, see Figure 3. In this research project it is implemented using Matlab Simulink Reinforcement Learning Toolbox. The trained agent is designed based on the Deep Deterministic Policy Gradient (DDPG) method within an actor-critic structure. In this work the training requested the performing of 500 episodes for achieving high cumulative reward. Its inputs are the observation signals from the environment and the calculated reward. The observed data are the vehicles' stations and velocity values. The reward is calculated based on the total distance driven from the beginning of the simulation and based on the difference between the actual acceleration and the $u_L$ value.

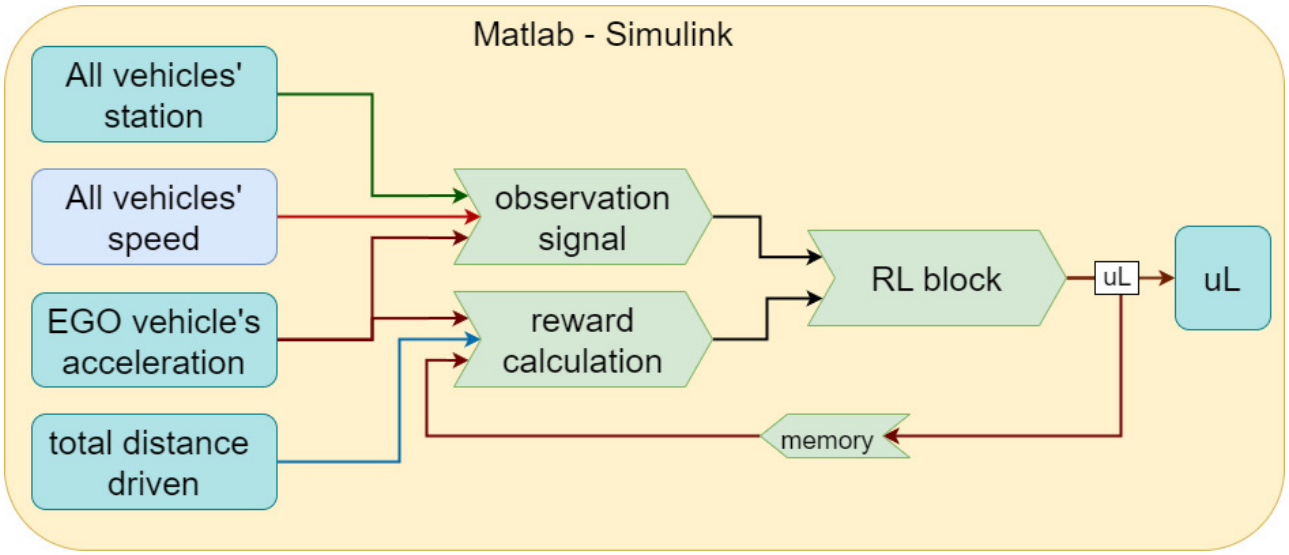


*Figure 3: The calculation of the learning-based acceleration*

## 3. Demonstrations

The presented algorithm was tested using Nissan Leaf test vehicle on a test track, where a roundabout was built up using cones. Although the operation of the algorithm has been tested under lots of different entering-exiting scenarios, i.e., the parameters of the roundabout is not fixed during the tests. In this paper only

one representative example is presented in order to show the effectiveness of the AV control operation. It consisted of a 1 lane roundabout with a radius of 10 m. It had 3 incoming and 3 outgoing roads, located 120° angular rotations after each other. The center lines of the roads and their IDs are shown in Figure 4. The environment vehicles were generated by MATLAB, and their routes were pre-set before the simulation started. Their position was used to calculate the station value, which was their distance to the next conflict point on their route, shown with green crosses in Figure 4. The AV's station value is also calculated and forwarded to the speed calculation algorithm, which outputs the EGO vehicle's desired velocity for the next time step. The description of the details of the test vehicle with AV functionalities can be found in Horváth and Pozna (2021). The demonstration set-up for illustrating virtual vehicles in AR can be found in Németh et al. (2023).

The demonstration also contained virtual AVs for simulating the environment. Their routes were also randomized, and their velocity profiles were set to constant velocity values. The goal for the AV was to drive safely to the roundabout, i.e. give way to other vehicles in the roundabout, and to maintain a safe distance from other vehicles, which were driving slower before the AV, during the whole test. The sides of the roads were marked with traffic cones in order that the pathway was made visible. The requirements against the test AV were to steer on the pre-defined route and move with the velocity computed by the presented own-developed control algorithm.

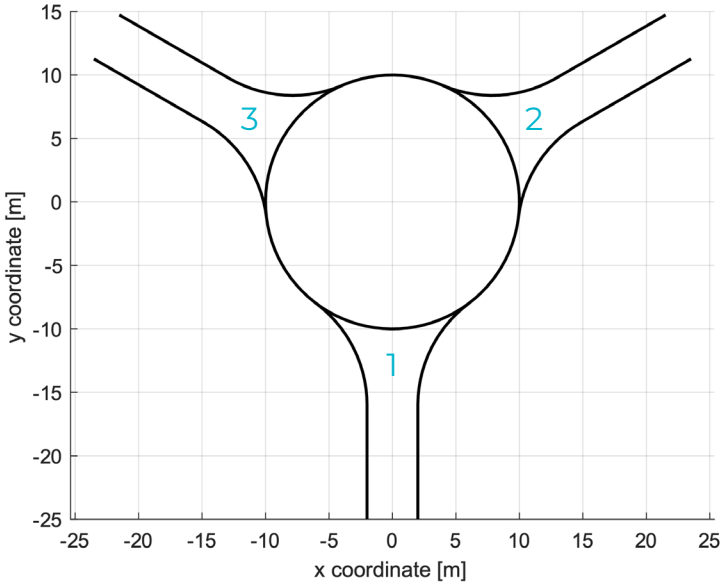


*Figure 4: The scheme of the roundabout in the test field*

## 3.1. Results

The performed tests showed that the test AV was able to follow the reference path, which is illustrated in Figure 5. During this scenario, the test AV vehicle was driven into and out of the roundabout using the road with ID 1. The simulation started from a standing position, i.e., the initial velocity of the AV was 0 m/s. The vehicle accelerated immediately after the start of the test. The maximum of the lateral error during path tracking was 0.83 m. This value was achieved when the test AV was entered into the roundabout. This is considered to be acceptable, because the lane of the roundabout is wide enough to tolerate this tracking error, i.e. the AV was not left the lane.

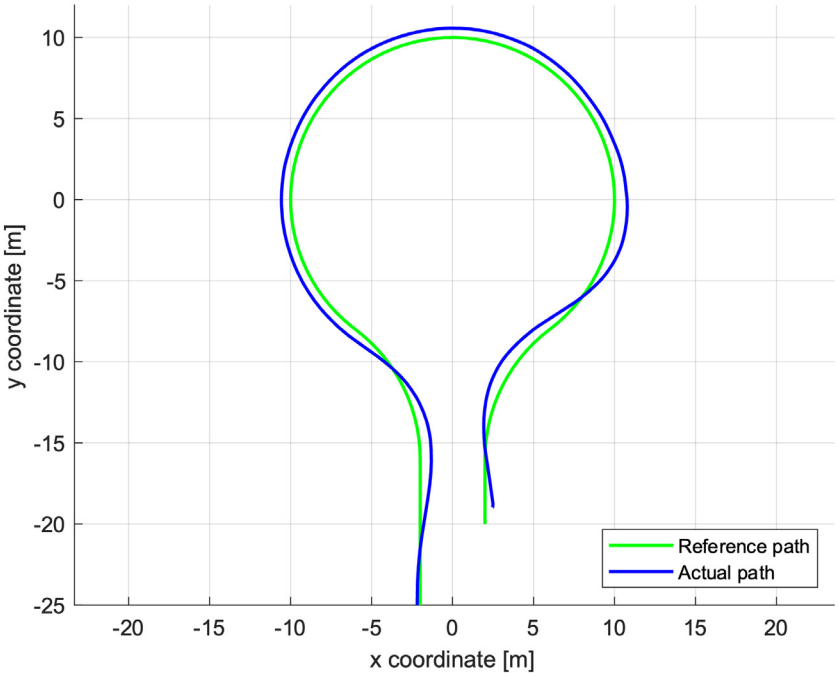


*Figure 5: The path of the AV*

The velocity profile of the test AV can be found in Figure 6. After the initialisation of the test AV velocity, the reference velocity of 0.25 m/s was achieved for approaching the roundabout entrance. The reason for accelerating to this low velocity was that one of the virtual vehicles arrived at Entrance 1; see the left image in Figure 7. Thus, the algorithm highlighted energy efficiency instead of insufficient acceleration and deceleration commands. The test AV was driven off at around 16 seconds after the simulation started. After that, the AV accelerated to reach the maximal allowed speed, 10 km/h. This was a safe speed to drive in the roundabout. After 43 seconds of the test, the vehicle caught up with a virtual vehicle in the roundabout and decreased its velocity to hold a safe distance behind it. Since that virtual vehicle had the same route to drive out from the roundabout as the test AV, it had to be followed; see the right image in Figure 7.

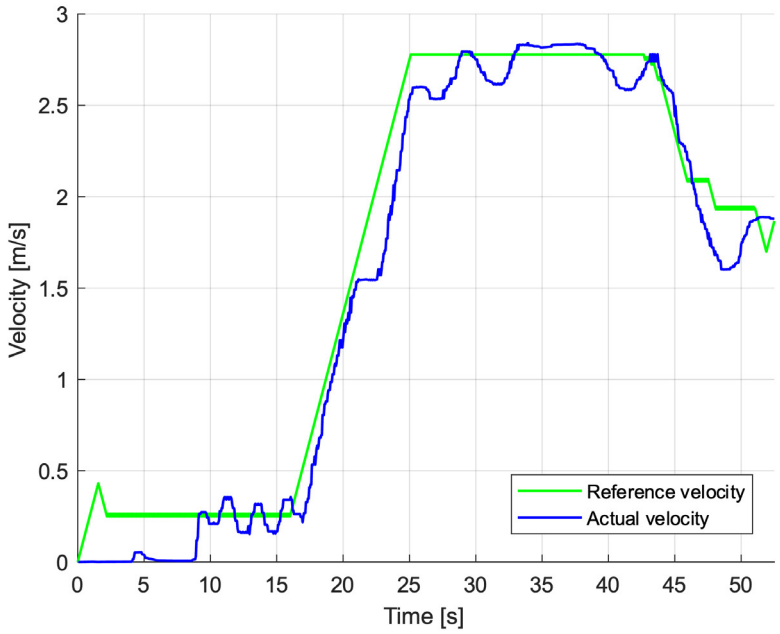


*Figure 6: The velocity profile of the AV during the test*

*Figure 7: Illustrations of the virtual vehicles' motion on the test track using real-time AR environment*

Figure 8 shows the distance between the test AV and the closest virtual vehicle in the environment. This metric has high important from the viewpoint of safety, such as to avoid collision. If this value was above 30m, it was not illustrated in Figure 8. It can be seen that the minimum value of the distance was 18 m when the test AV was driven into the roundabout, i.e., the approaching manoeuvre was safe, see 16s in Figure 8. Moreover, when the test AV approached the virtual vehicle in the roundabout, it moved closer to the preceding vehicle. In order to keep a predefined distance, the test AV started to brake when it was closer than 13.5 m, which resulted in an energy-efficient motion profile, see Figure 6. Nevertheless, the distance between the vehicles was never below 6.4 m, which is considered to be safe.

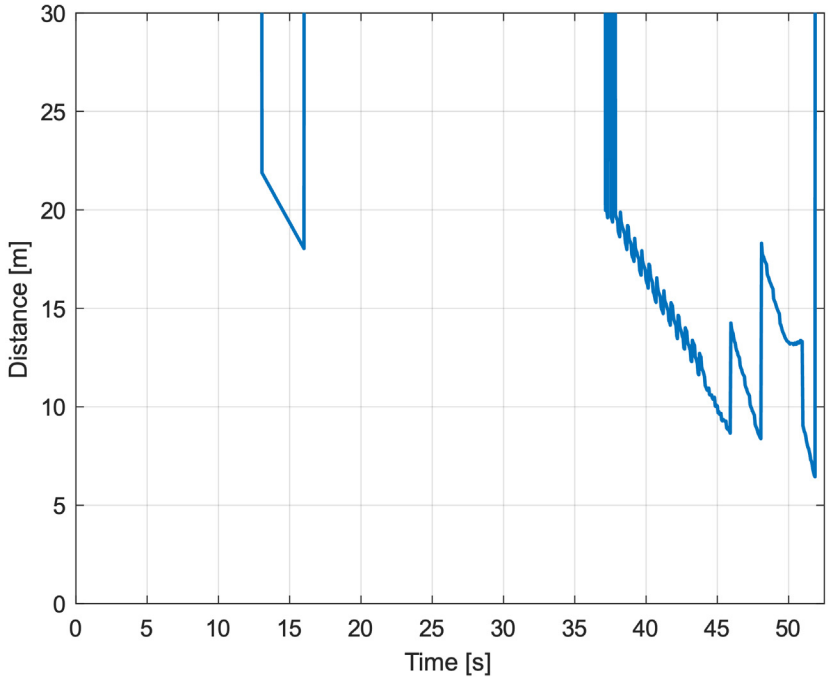


*Figure 8: The distance to the closest virtual vehicle in the environment*

# 4. Conclusion

The presented test result shows that the AV is able to move with a safe and energy-efficient velocity profile, and the proposed learning-based algorithm can be implemented. The presented investigation shows that the initial test of the algorithm was successful, which provides a basis for performing further tests in Zala-Zone Automotive Proving Ground. The algorithm and the demonstration setup contribute to sustainability from two viewpoints. First, the energy-efficient nature of the learning-based method provides a solid basis for working out a general motion profile generation algorithm under complex urban driving scenarios. Second, the demonstration setup has reduced the cost of testing AV functionalities in real time. Its reason is that it does not require the involvement of further test vehicles, but the motion of virtual vehicles can be illustrated in the physical environment in real-time.

## Acknowledgements

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# IMPROVING PTZ CAMERA CONTROL FOR SURVEILLANCE USING PROXIMAL POLICY OPTIMIZATION

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**This paper presents advancements in camera-only surveillance systems, focusing on the integration of Proximal Policy Optimization (PPO) and its recurrent variant to improve the detection and tracking capabilities of PTZ cameras. Building on previous research, we refine our PPO model by adjusting observation representations and hyperparameters, significantly improving target coverage and tracking accuracy. The study evaluates two simulated scenarios, an abstract grid-like environment and a more realistic scenario with predefined intruder paths. The results demonstrate that the standard PPO outperforms both the heuristic and recurrent models. The findings confirm the potential of Reinforcement Learning (RL) in improving autonomous surveillance systems but also point to the need for more complex simulation environments to fully exploit the capabilities of recurrent neural networks.**

## 1. Introduction

In modern security systems, effective surveillance plays a critical role in both preemptive and reactive safety measures. Traditional surveillance methods or simple automated systems heavily rely on human intervention. They are no longer sufficient to address the complexities of modern security threats. The integration of artificial intelligence, particularly through RL, is a potential enhancement for autonomous and efficient monitoring solutions.

In recent literature, dynamic control of PTZ cameras using RL has been explored by Fahim et al. (2023), who demonstrated improvements in balancing detailed observation with broad area coverage. Bisagno et al. (2020) optimized the dynamic reconfiguration of camera networks for crowd surveillance using a decentralized RL approach. Fang et al. (2022) significantly enhanced target coverage by optimizing camera poses in a multi-camera system using a centralized multi-agent RL approach. In contrast to these approaches that utilize custom-built simulations with image-based inputs, this study adopts a simplified model where targets are represented as points in a coordinate system—an abstraction that has all the fundamental aspects of target coverage and camera coordination. This modeling approach is in line with recent research directions like the Multi-Agent Tracking Environment (MATE) introduced by Pan et al. (2022), which serves as a framework for multi-agent target coverage. Chen et al. (2024) integrated Monte Carlo Tree Search with target motion modeling, enabling efficient and dynamic camera movement to improve multi-target tracking. The work of Wang et al. (2021) is closely related to our research. They developed a hierarchical reinforcement learning framework that enhances target coverage efficiency in multi-agent environments. Their approach utilizes a two-level policy structure to optimize target-agent interactions, demonstrating a significant enhancement in managing and coordinating multiple agents effectively.

Building upon our previous research that explored hybrid monitoring systems using Pan-Tilt-Zoom (PTZ) cameras and Unmanned Aerial Vehicles (UAVs) (Darázs et al., 2024), this paper advances camera-only surveillance systems. We extend our prior work by refining our PPO model, incorporating new observation representation and hyperparameters to improve target coverage and tracking rates.

This study aims to enhance the detection and tracking capabilities of PTZ cameras through an improved PPO model and to explore the use of Recurrent PPO to capture temporal dynamics of intruder movements within our multi-agent simulation. Specifically, our contributions are twofold: firstly, we demonstrate how adjustments to the observation representation and hyperparameters can significantly refine the performance of standard PPO models in a surveillance context. Secondly, by incorporating Recurrent PPO, we assess its effectiveness over traditional PPO.

The rest of the paper first details the simulation environments in Section 2. and describes the algorithms developed in Section 3. The experimental setup and the results are discussed in Section 4 and 5, before concluding the work in Section 6.

## 2. Simulation Environment

The simulation environment was designed to test the performance of surveillance algorithms under two distinct scenarios:

- **Abstract** Scenario: This scenario represents a generalized setup where intruders are equally likely to appear at any point within a dense grid-like environment.
- **Real** Scenario: This scenario simulates a more realistic environment where intruders follow predefined paths, similar to patterns observed in real world settings.

Both scenarios are depicted in Figure 1, illustrating the layout of intruder movements.

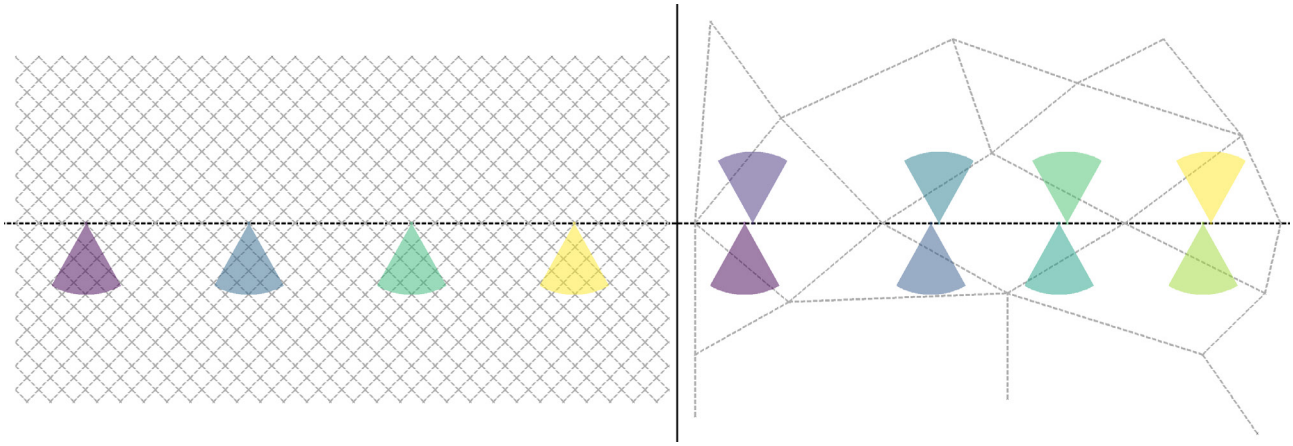

*Figure 1. Abstract Environment on the left, Real Environment on the right*

Intruders are modeled to move in organized groups, this reflects patterns seen in the real world. Groups of intruders, ranging from 5 to 30 members, are initialized randomly throughout the simulation, moving upwards from the bottom. Over the course of the simulation, these groups exhibit dynamic behaviors such as splitting into smaller groups or merging with other intruder groups. Each intruder within a group is modeled individually, necessitating that algorithms identify and track each target separately.

The camera sensors are modeled as directional, sector-shaped polygons with a horizontal field of view and a fixed detection range of 220 units. They rotate at a speed of 90 °/s, with a simulation step interval of 0.25 s. The effectiveness of these cameras in detecting intruders is determined using a binary detection model, specifically the Target in Sector (TIS) test (Guvensan et al., 2011):

$$\|v\|_2 \leq R_c \wedge d^T v \geq \|v\|_2 cos\left(\frac{\theta}{2}\right) \quad (1)$$

where $v$ is the vector from the camera to the intruder, $d$ is a unit vector representing the direction the camera is facing, $R_c$ and $\theta$ and denote the camera's maximum detection range and field of view. This binary detection model ensures that a target is detected if it is within the detection range and field of view of the camera.

# 3. Algorithms

In this section, two algorithms are described, a simple heuristic-based method from Darázs et al. (2024), and an improved RL based method.

## 3.1. Dynamic Surveillance and Tracking Algorithm (DSTA)

The surveillance algorithm implemented in this work operates in two primary modes: "scanning" and "tracking". Both modes are designed to optimize the coverage area while efficiently detecting and tracking intruders in each environment. We named this baseline algorithm Dynamic Surveillance and Tracking Algorithm (DSTA).

### Scanning Mode

This mode is the default state of the cameras. In this mode, each camera cycles through a set of predefined orientation points at specific time intervals. These fixed points are strategically chosen to maximize field coverage, ensuring a systematic scan of the environment. Figure 2. shows the orientation points (in the Real environment the orientation points of the camera pairs are mirrored). The goal is to detect any potential intruders entering the surveillance area.

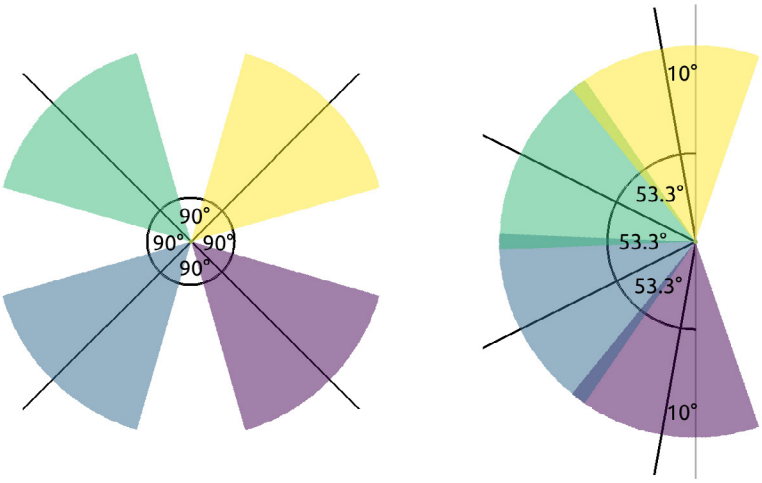


*Figure 2. Orientation points for each camera: Abstract on the left, Real on the right*

### Tracking Mode

Upon detecting an intruder during the scanning phase, the system switches to tracking mode. This mode is more dynamic and focuses on monitoring detected intruders. To manage the complexity of tracking multiple targets, detected individuals are grouped into clusters based on their proximity. This clustering is achieved through a greedy algorithm following Wang et al. (2018) aimed at solving the minimum circle cover problem, where each cluster of intruders is enclosed within a minimum bounding circle. The center of these circles then becomes the focal point for the tracking process.

Once the focal points are determined, each camera calculates the cost to maintain surveillance on these points. The cost is a function of two factors: the distance from the camera to the focal point (denoted as $d$), and the angular rotation needed from the camera's current orientation to align with this point (denoted

as $\theta$). The formula for the cost is given by $C=d+\alpha\cdot\theta$, where $\alpha$ is a weighting parameter that balances the importance of distance versus angular adjustment. We found $\alpha=1$ to be an effective choice in our simulations.

To optimize the surveillance process, the system solves a minimum-cost assignment problem at each time step according to Ramshaw et al. (2012). In this problem, the nodes representing cameras are matched with nodes representing intruder clusters such that the total cost of surveillance (based on the previously calculated costs) is minimized across all cameras. This ensures that each camera is utilized efficiently, focusing on the clusters that are most cost-effective to monitor.

### Switching between Modes

The algorithm is designed to switch back to scanning mode after a predefined time, or after successfully tracking the current targets. This is to ensure that while focusing on known intruders, the system does not miss new targets.

This dual-mode operation ensures relatively good coverage and tracking of intruders, making use of camera capabilities to maintain surveillance across varying scenarios in our simulated environments.

## 3.2. Multi-agent reinforcement learning

Our study employs a PPO algorithm (Schuman et al., 2017), which is a state-of-the-art policy-gradient method. The primary objective of PPO is to perform minor updates to ensure that successive policy versions remain close to each other. The problem is formulated as multi-agent RL, where each camera is controlled by an individual PPO agent. In our system, each surveillance camera operates as an independent agent under the multi-agent RL framework. We adopt a parameter-sharing strategy in the training process, which is suitable for homogeneous environments where agents must perform similar tasks (Gupta et al., 2017).

### Network Architecture

The underlying network for each PPO agent is a Multi-Layer Perceptron (MLP) with two hidden layers containing 128 and 32 neurons. To enhance the capability of our model to handle temporal sequences, we also experimented with a Recurrent PPO variant. This version incorporates a Long Short-Term Memory (LSTM) layer with 32 hidden states, combined with an MLP output layer.

### Observation Space

Previously (Darázs et al.,2024), intruders were represented in Cartesian coordinates. In contrast, the updated model uses polar coordinates relative to each camera position. This is found to generalize better across all scenarios. Observations for each agent include:

- The normalized distance and angle to each intruder from the camera.
- The camera's current yaw direction.
- In scenarios with overlapping camera fields (Real Environment), the yaw directions of neighboring cameras.
- A one-hot encoded vector identifying the camera.

Each intruder is represented by their normalized distance and angle, leading to an observation vector padded or truncated to handle up to 200 intruders. This results in a total of 409 input features for the Abstract environment and 410 for the Real environment.

### Reward function

Each camera agent's objective is to maximize its coverage of intruders. The local reward, $r_i^{cov}$, calculated by the ratio of observed intruders, $N_i^{observed}$ , to the potential intruders within its range, $N_i^{potential}$:

$$r_i^{cov} = \frac{N_i^{observed}}{N_i^{potential}} \tag{2}$$

To discourage unnecessary camera movements, a rotational penalty $r_i^{move}=\gamma\theta_i$ is subtracted from the local reward, where $\theta_i$ is the angle rotated at the timestep and $\gamma$ is the penalty coefficient. The penalty coefficient is set at 0.004 and 0.002 in the Abstract and Real environments. The local reward for each camera is then defined as:

$$r_i^{local} = r_i^{cov} - r_i^{move} \tag{3}$$

In the Abstract environment, where camera fields do not overlap, only the local reward is used. In contrast, in the Real environment, where cameras are paired, the global reward, $r_i^{global}$, is calculated similarly to the local reward but aggregates the coverage across the pair of cameras:

$$r_i^{globalcov} = \frac{\sum N_i^{observed}}{\sum N_i^{potential}} \tag{4}$$

where the summation is performed over both members of the pairs.

### Total Reward Calculation

The total reward for each camera combines these elements differently based on the environment. In the Abstract environment, the total reward $r_i$ is purely the local reward $r_i^{local}$, while in the Real environment the total reward for each camera in a pair is solely the global reward $r_i^{global}$ calculated across camera pairs.

## 4. Experimental setup:

We tested the approaches in both environments. The tests were run for 1500 simulation steps to have reasonable confidence in the performance metrics. The camera had a rotation speed of 90 °/s and the invaders' walking speed is set to 25 units of distance. To evaluate the algorithms, we introduced four performance indicators:

- **Average Tracking Ratio:** The average time an intruder was detected by any sensor as a proportion of its total time in the detection field.
- **Average Coverage:** Calculated at each simulation step as the ratio of detected intruders to the total number present, averaged over the simulation duration.
- **Ratio of Non-Observed Intruders:** The proportion of intruders who went undetected throughout their presence on the field.
- **Average Camera Capacity Utilization:** Reflects camera activity, quantified by the amount of camera rotation relative to its maximum capacity.

These metrics provided a comprehensive evaluation of the detection algorithms from both efficiency and operational cost perspectives. The PPO and Recurrent PPO agents were chosen after careful hyperparameter tuning after convergence, the exact hyperparameters can be found in Table 1.

*Table 1: PPO training hyperparameters*

| Parameter | Values |
|---|---|
| learning rate | $2\times10^{-4}$ |
| total_timestep | 3,000,000 |
| n_steps | 256 |
| n_envs | 8 |
| batch_size | 256 |
| n_epoch | 18 |

# 5. Results

The performance outcomes of our analysis are summarized in Table 2, where ↑ and ↓ indicate if larger or smaller values are better. The results clearly show that the PPO agent significantly outperformed the heuristic DSTA across both the ABSTRACT and REAL environments in terms of tracking and coverage.

*Table 2: Performance indicators*

| | Average tracking ratio ( ↑ ) | | Average Coverage ( ↑ ) | | Non-observed ratio ( ↓ ) | | Avg. camera util ( ↓ ) | |
|---|---|---|---|---|---|---|---|---|
| | Abstract | Real | Abstract | Real | Abstract | Real | Abstract | Real |
| DSTA | 0.2558 | 0.4314 | 0.2497 | 0.4253 | 0.1900 | 0.0000 | 0.1832 | 0.1448 |
| PPO | 0.4369 | 0.6272 | 0.4918 | 0.6686 | 0.0618 | 0.0565 | 0.3417 | 0.3362 |
| Recurrent PPO | 0.3792 | 0.6080 | 0.4369 | 0.6181 | 0.1036 | 0.0146 | 0.2463 | 0.4391 |

While DSTA showed lower camera utilization, suggesting less frequent movements, it was less effective in terms of coverage and tracking. This indicates the trade-off between minimizing camera movements and maximizing detection. Unexpectedly, the Recurrent PPO did not surpass the performance of the non-recurrent PPO model. The analysis of this phenomenon suggests that the simulation environment might be responsible for it.

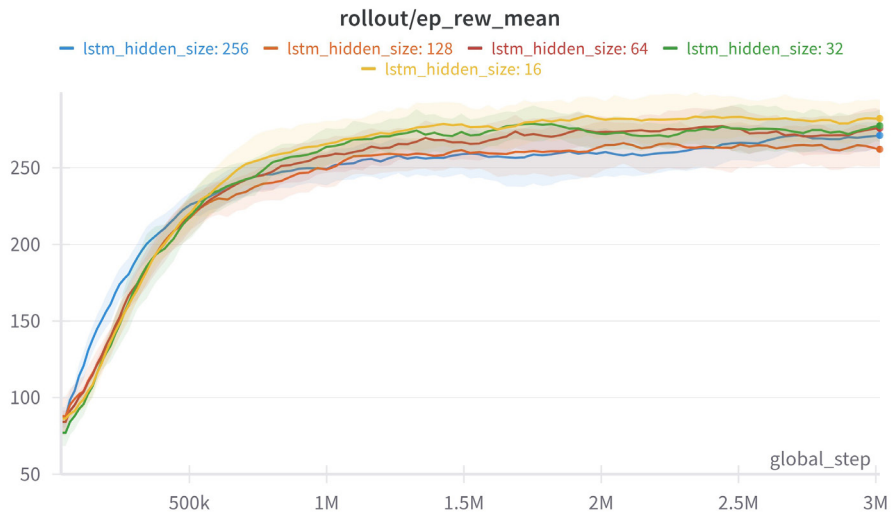


*Figure 3: Average episode reward with different LSTM hidden size*

The environment is structured such that intruders always initiate from the bottom and move upwards. In scenarios where an intruder splits from a group within sight, a non-recurrent PPO agent following one target (say, intruder A) loses sight and hence the 'memory' of intruder B. The recurrent variant has the knowledge of intruder B but, due to the intruder's behavior, by the time intruder A is out of detection range, intruder B is probably also out of detection range, making the memory practically useless. This means that while the environment state is non-Markovian, the optimal decision-making does not significantly benefit from full historical knowledge. Instead, it only requires knowledge of a few recent states. Figure 3. also suggests this, where a smaller hidden size in the LSTM layer performs better than larger ones. These insights highlight that the Recurrent PPO's potential is not fully realized in our current setup due to the specific dynamics and simplicity of intruder movements. Future work may explore more complex intruder behaviors, where longer-term memory could become more beneficial.

# 6. Conclusion

In conclusion, our research has demonstrated the enhancement of PTZ camera surveillance through the application of a PPO model and its recurrent variant. By adjusting observation representations and hyper-parameters, we have achieved significant improvements in target coverage and tracking rates, illustrating the potential of advanced RL techniques in complex surveillance scenarios. Although the Recurrent PPO model did not outperform the standard PPO as anticipated, this finding provides valuable insights into the dynamics of the environment and highlights the importance of intruder behavior modeling.

Future studies will explore more complex scenarios where long-term memory and advanced RL strategies could yield greater benefits. Incorporating additional AI techniques such as MCTS could further enhance the system's adaptability and efficiency in real world surveillance applications.

# Acknowledgments

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# CONTINUOUS MAP-AWARE PARTICLE FILTER IN OFF-ROAD ENVIRONMENT

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**Accurate localization is a persistent challenge in mobile object tracking, particularly in environments characterized by uneven sensor coverage and inconsistent sensor reliability. This study explores the integration of map-aware particle filters, leveraging map data to enhance positioning accuracy by assigning higher probabilities to positions near defined paths and lower probabilities to off-road locations. Experiments are made in a simulated environment to test the filters under different sensor reliability. A comparative analysis with traditional particle filtering methods demonstrates that the map-aware approach, when appropriately parameterized for the given environmental condition, significantly improves positioning accuracy, emphasizing its potential for enhancing mobile tracking performance in complex environments. The two proposed methods, DMAPF and CMAPF are also compared under multiple scenarios.**

## 1. Introduction

Precise localization is critical for applications ranging from autonomous navigation to wildlife monitoring. Traditional methods rely heavily on sensor data, which can be sparse or irregularly timed, often leading to tracking errors. The Kalman filter, introduced in the mid-20-th century, advanced sensor fusion but has limitations under non-linear or non-Gaussian conditions common in real-world scenarios. The Particle Filter (PF) offers more flexibility in handling such complexities, making it suitable for scenarios where assumptions of linearity and normality do not hold. Elevating the capabilities of particle filters, map-aware filters incorporate static map data directly into the filtering process.

A simulated environment is made in order to test different scenarios. The aim is to compare the performance of filters under reliable, high precision sensor data with sparse, inaccurate sensors. Two map-aware particle filters are introduced, the discrete map-aware filter DMAPF investigates whether a particle is on the road or not and adjusts its weight accordingly, and the continuous CMAPF, considering the distance from the nearest road and adjusting weights with exponential decay of that distance. Different parameters of these filters are tested and analysed, so that appropriate parameters can be found later, based on the sensor precisions, average distances of the tracks from the nearest roads, and the emphasis on the map-awareness.

The remainder of this paper is structured as follows: in Section 2 we overview the relevant literature. Section 3 introduces the theory behind Bayes and Particle filters and extends the original algorithm to incorporate map-related data. Section 4 presents our experiments and results, while Section 5 offers our conclusions.

## 2. Related works

The idea of involving map data into the filtering process is not new. In (Mansour and Waters, 2013) the digital map is segmented into two disjoint set of feasible and infeasible areas. For example, in vehicular navigation buildings and parks are infeasible areas. If the estimated position provided by a Kalman filter fall

in an infeasible area, then it needs to be projected onto a feasible region. This projection is taken to be an extra measurement and the covariance matrix of the Kalman filter is adjusted accordingly. In (Widyawan et al., 2007) a similar approach is used in the case of particle filtering in an indoor localization scenario. Here, particles that would move across a wall or other solid objects are eliminated. In (Widyawan et al., 2008) building upon this method a backtracking algorithm was developed that refines previous state estimates by leaving out those particles from the estimation whose movement proved to be illegitimate in a future step. The authors of (Peker et al., 2011) in their vehicle localization system leveraged a categorization of roads to fine-tune the weights assigned to the particles based on their speed. They relied on heuristics such as fast-moving objects are unlikely to use residential roads. (Min Oh et al., 2004) introduced map-awareness seen as a new detection, by defining regions with different properties, and biasing the motion model toward areas of higher probability. The rest of papers all rely on the framework developed in (Gustafsson et al., 2002) for positioning, navigating, and tracking with particle filters.

# 3. Methodology

## 3.1. Bayesian filter

Particle filter is a specific instance of a more general method known as Bayesian filter or Recursive Bayesian Estimation. The target state $\boldsymbol{x_t}$ evolves according to the following discrete-time stochastic model: $\boldsymbol{x_t=f(x_{t-1})+v_t}$, where $\boldsymbol{f}$ is a possibly non-linear function and $\boldsymbol{v_t}$ is the process noise, typically assumed to be drawn from a known distribution. The measurement $\boldsymbol{z_t}$ relates to the state through $\boldsymbol{z_t=h(x_t)+w_t}$, where $\boldsymbol{h}$ is another possibly non-linear function and $\boldsymbol{w_t}$ is the observation noise, also assumed to be drawn from a known distribution.

The aim is to calculate the posterior distribution $\boldsymbol{p(x_t|z_{1:})}$, the current state $\boldsymbol{x_t}$conditioned on all measurements up to time $\boldsymbol{t}$. This is achieved in two steps. By the Bayes rule this can be expressed as

$$p(x_t|z_{1:t}) \propto p(z_t|x_t)p(x_t|z_{1:t-1}), \tag{1}$$

the product of the predictive distribution $\boldsymbol{p(x_t|z_{1:t-1})}$ and the measurement model $\boldsymbol{p(z_t|x_t)}$ (up to a constant factor). The former can be computed as

$$p(x_t|z_{1:t-1}) = \int p(x_t|x_{t-1})p(x_{t-1}|z_{1:t-1})dx_{t-1} \tag{2}$$

by integrating the motion model $\boldsymbol{p(x_t|x_{t-1})}$ over posterior $\boldsymbol{p(x_{1:t-1}|z_{1:t-1})}$. By receiving measurement $\boldsymbol{z_t}$ Eq(1) and Eq(2) obtains the Bayes filter:

$$p(x_t|z_{1:t}) = kp(z_t|x_t)\int p(x_t|x_{t-1})p(x_{t-1}|z_{1:t-1})dx_{t-1} \tag{3}$$

Relying on the posterior distribution, the new state $\boldsymbol{x_t}$ can be estimated in different ways. For example, $\boldsymbol{x_t=\int x\, p(x_t|z_{1:t})dx_t}$ results the minimum mean-squared error.

## 3.2. Particle filter

However, Eq(3) cannot be calculated analytically. A numerical approximation to Bayes Filter can be implemented by use of Sequential Monte Carlo methods, also known as particle filters (PF). The sampling importance resampling (SIR) algorithm is one of the most widely used sequential Monte Carlo methods, which allow system state estimates to be computed on-line while the state changes as it is the case for tracking algorithms. An SIR filter usually manages a fixed number of possible system state hypotheses $\boldsymbol{x^{(i)}}$, also called particles. Ideally, these particles approximate the distribution of the system state, $\boldsymbol{p(x_t)}$. The SIR algorithm stages iterated over discrete time steps.

More concretely, Particle Filter approximates the posterior distribution $p(x_t | z_{1:t})$ using a set of $N$ particles $\{x_t^{(i)}\}_{i=1}^N$ and their associated weights $\{w_t^{(i)}\}_{i=1}^N$. The key idea is to estimate $x_t$ with the weighted sum of these particles:

$$\bar{x}_t = \frac{1}{N}\sum_{1}^{N} w_t^{(i)} x_t^{(i)} \tag{4}$$

The basic algorithm goes as follows, see Algorithm 1. for reference. At $t = 0$, the filter initializes the particles rom the prior distribution $p(x_0)$:$x_0^{(i)} \sim p(x_0)$ with weights $w_0^{(i)} = 1/N$. For each particle $x_{t-1}^{(i)}$ at time $t-1$, the filter propagates it through the process model to generate the predicted particles: $x_t^{(i)} \sim p(x_t | x_{t-1}^{(i)})$. . This involves sampling from the process model $f$ with the process noise $v_t$.

Upon receiving a new observation $z_t$, the filter updates the weights of the particles using the likelihood of the observation given the predicted state: $w_t^{(i)} \propto w_{t-1}^{(i)} p(z_t | x_t^{(i)})$. These weights are then normalized so that they sum up to 1. $x_t$ then can be estimated using Eq(4). This ensures that particles aligned with higher observation likelihoods have more influence on the estimated state.

To avoid degeneracy, where most particles have negligible weights, the filter performs resampling when the effective sample size given by $N_{\text{eff}} = 1/\sum_{i=1}^{N}\left(w_t^{(i)}\right)^2$ falls below a threshold. If resampling is needed, a new set of particles is generated by sampling with replacement from the current set, with probabilities proportional to their weights, and the weights are reset to $1/N$.

*Algorithm 1. A pseudo-code of our proposed Map-Aware Particle Filter algorithm*

| | Particle Filter algorithm (Map-Aware version) |
|---|---|
| 1. | Initialize particles from the prior distribution $p(x_0)$: $x_0^{(i)} \sim p(x_0)$ and weights $w_0^{(i)} = 1/N$ |
| 2. | While receiving new detection $z_t$: |
| 3. | Predict: propagate particles according to motion model $x_t^{(i)} \sim p\left(x_t \middle| x_{t-1}^{(i)}\right)$ |
| 4. | Update: update weights of particles using the predicted state: $w_t^{(i)} \propto w_{t-1}^{(i)} p\left(z_t \middle| x_t^{(i)}\right)$ |
| 5. | Map-Aware update $p\left(M \middle| x_t^{(i)}\right)$: calculate and update weights: $w_t^{(i)} = w_t^{(i)} p\left(M \middle| x_t^{(i)}\right)$ |
| 6. | Estimate: $\bar{x}_t = \frac{1}{N}\sum_1^N w_t^{(i)} x_t^{(i)}$ |
| 7. | Resample: resample from particles with replacement if $N_{\text{eff}} \leq N/2$ |

## 3.3. Map-Aware Particle Filters

To enable Particle filter to include map related information, this data can be considered as a set of new measurements (Rechy et al., 2018). Denote map information with $M$. In most real scenarios $M$ is independent from all other $z_{1:t}$ measurements at any time , therefore the measurement model satisfies

$$p\left(M, z_t \middle| x_t^{(i)}\right) = p\left(M \middle| x_t^{(i)}\right) p\left(z_t \middle| x_t^{(i)}\right) \tag{5}$$

This means that the new weights can be calculated as the product of the map topology aware measurement model and the old measurement model, see Algorithm 1. line 5. The relation of the two terms on the right-hand side control this filter's preference of map-awareness over real sensor data.

One approach is to modify the weights of each particle according to the distance from the nearest road.

Let $d^i$ denote the distance of the th particle from the nearest road. Note that for particles on road it is 0. Our aim was to assign higher likelihoods to positions near defined paths and lower probabilities to off-road locations. The Discrete Map-Aware Particle Filter with parameters $\mu_1, \mu_2$, abbreviated as $DMAPF(\mu_1, \mu_2)$ multiplies weights of particles on road with $\mu_1$, and with $\mu_2$ off-road ones, then normalizes. If a track is expected to stay on road (as is the case for vehicles for instance) assigning parameters so the ratio $\mu_1/\mu_2$ (called the road dominance value) is large may lead to better performance, as it will reward particles on road.

There are paths however that may deviate from road or cases when due to unreliable sensor data particles have harder time staying on track. This is where Continuous Map-Aware Particle Filter with parameter $\lambda$, abbreviated as $CMAPF(\lambda)$. A tolerance level is introduced, taking into account the amount of deviation from nearest path by the inverse exponential function.: $p\left(M\middle|x_t^{(i)}\right) = Kexp(-\lambda d^i)$, for $\lambda > 0$, and normalizing constant $K$. By this the concentration of the particles increases in regions where the map indicates a high likelihood for objects to be located, and decreases in low likelihood areas, thereby biasing predictions to remain on roads. With unreliable sensor data, but under the hypothesis of staying on road, this is expected to improve the performance of filters, letting particles only slightly deviate from road. Note however, this approach may also lead to suboptimal predictions when tracks largely deviate from roads, because for large $\lambda$ values at long distance the inverse exponential is negligible. To address this, road dominance can be extended to this case, by comparing $exp(-\lambda d_1)$ to $exp(-\lambda d_2)$ at distances $d_1$ and $d_2$. Hypotheses above suggests that both $\mu_1, \mu_2$ and $\lambda$ must be chosen carefully to balance these effects.

# 4. Experiments and results

## 4.1. Experiments

The MAPF's effectiveness was tested on two simulated tracks: one mostly stayed on the road representing a vehicle, while the other stayed off road at an average distance of 10 metres from nearest road, representing a person (see Figure 1). A handcrafted 2D map represented various terrains (e.g., roads, fields, forests), with both tracks set to the default terrain type. Three sensors, differing in update frequency and measurement accuracy, were used. The first provided high-frequency but essential long-term tracking, the second offered medium frequency with moderate accuracy, and the third delivered low-frequency, precise short-term tracking. The performance of CMAPF and DMAPF was compared to that of Particle filters. Since multiple sensors were used, at each time step their measurements had to be fused. To achieve this Eq(6) was utilized, assuming normal noise for all sensors:

$$z_{fused} = \frac{\sum_i \left( z_i \cdot \frac{1}{(\sigma_i)^2} \right)}{\sum_i \frac{1}{(\sigma_i)^2}}, \qquad \sigma_{fused} = \frac{1}{\sqrt{\sum_i \frac{1}{(\sigma_i)^2}}} \tag{6}$$

where $\sigma_i$ denotes the sensitivity of sensor $i$. If a sensor did not send measurements at time step $i$, then $z_i$ was taken to be 0. It is easy to calculate that the standard deviation of the fused detection is indeed $\sigma_{fused}$. Thereby detections of more reliable sensors contribute more to the fused detections.

Let $\varphi_{fused}$ denote the probability density function of the normal distribution $N(0,\sigma_{fused})$. The measurement model is calculated as $p\left(z_t\middle|x_t^{(i)}\right) = \varphi_{fused}\left(z_t - x_t^{(i)}\right)$. This assigns similar values for detections with high value, because no strict measurement update can be made from unreliable sensors, while assigns high weight for particles that are close to the detections, and negligible ones for others, for a small $\sigma_{fused}$ value.

The number of particles were set to $N = 5000$, since larger values did not improve the accuracy of either of the Particle filters significantly. Resampling threshold was set to $N/2$. The prior distribution was given by a Gaussian distribution around first detection, the motion model was the constant velocity model.

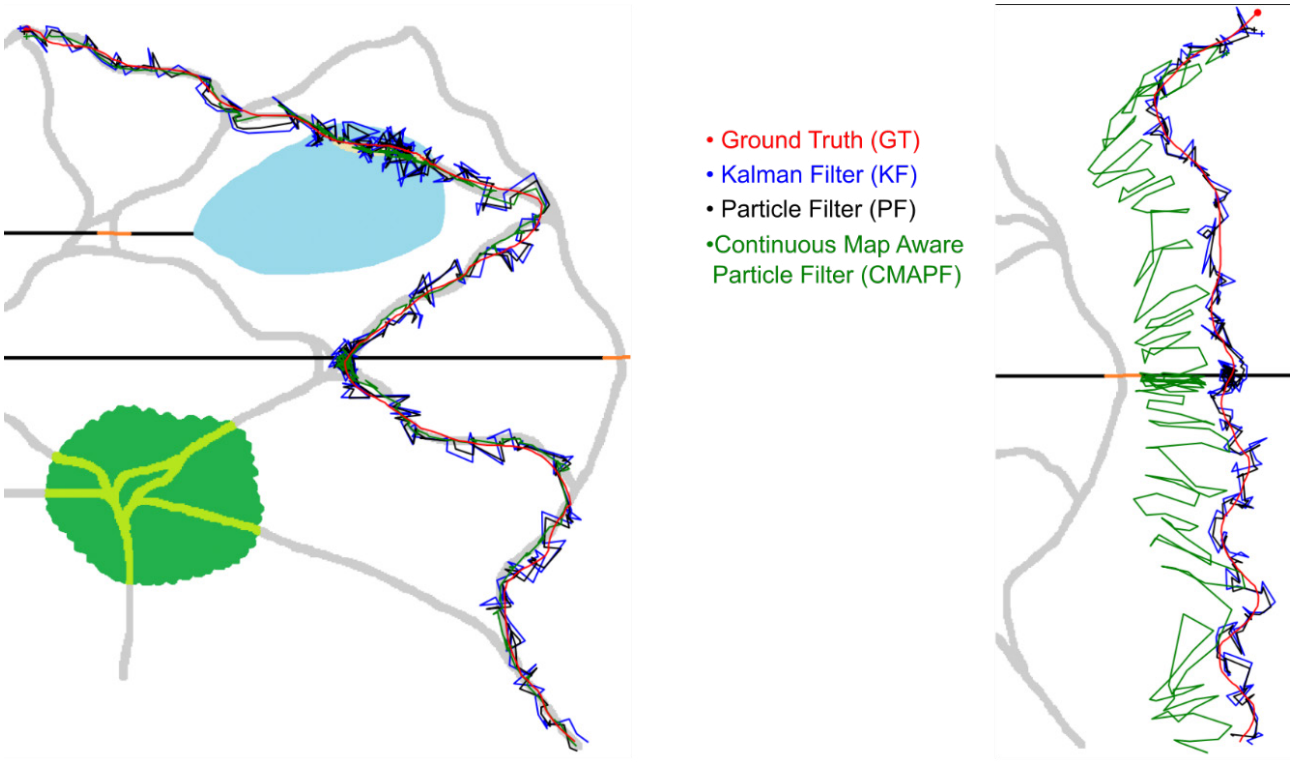


*Figure 1 (a) The on-road simulation. , the standard deviations of the sensors are [5, 3.5, 2.5]. (b) The off-road simulation. The standard deviations and  have the same values as in (a).*

## 4.2. Results

Rooted mean squared error distance of the estimated track from the ground truth (GT) path is considered for evaluation. For each map-aware filter we tested a variety of options to identify the certain behaviours and aspects.  Results of the simulations are shown in Table 1, the errors are in metres.

Overall, smaller sensor errors led to better filter performance on both tracks, while higher sensor errors degraded performance across all filters. Map-aware filters consistently outperformed traditional Particle filters, given appropriate settings.

In the on-road scenario, all Map-Aware Particle filters outperformed the traditional Particle filter, emphasizing the benefit of incorporating map data. This advantage became more pronounced as sensor reliability decreased. CMAPF(0.1) was the most precise, outperforming DMAPF across all four sensor reliability levels by 2.5%, 5.2%, 8.6%, and 5.8%, respectively. CMAPF(0.1) effectively balanced deviations, with road dominance of 1.649 at 1 meter to 5 metres, penalizing deviations due to sensor errors less aggressively than CMAPF(1), which had a 54.60 road dominance ratio at aforementioned distances. This highlights the importance of choosing an appropriate parameter, as other CMAPF settings underperformed compared to DMAPF. Notably, DMAPF methods provided more consistent performance, and even slight road dominance in DMAPF(1.1,1) yielded better results than the baseline Particle filter.

In the off-road scenario, DMAPF's uniform weighting for off-road particles led to performance similar to the traditional Particle filter, with slight variations based on sensor reliability. Higher sensor errors caused more particles to deviate closer to roads, reducing accuracy when using high road dominance values (e.g., DMAPF(10,1)). This suggests that lower road dominance is preferable with greater sensor errors. All CMAPF models underperformed compared to both traditional Particle filters and DMAPF off-road, due to unbalanced particle weighting. CMAPF(0.001) - with a road dominance ratio of 1.01 at 1 to 10 m - nearly matched traditional Particle filter performance, effectively approximating the Particle filter. Higher parameter CMAPF

models excessively reduced the weights of correct particles due to their distance from roads, resulting in biased predictions. For example, CMAPF(0.1), which excelled on-road, has a road dominance of 2.78 at distances 5 to 15 m, leading to less accurate off-road tracking than DMAPFs. This effect is evident in Figure 1, where CMAPF(0.1) follows the track smoothly in (a), but struggles in (b) due to aggressive weighting and high sensor sensitivities, resulting in a more erratic trajectory.

*Table 1: The RMSE errors of the different filtering methods. (a) On-road scenario, (b) off-road scenario. refers to the three sensor sensitivities. Errors are in metres.*

| | On-road track | | | | Off-road track | | | |
|---|---|---|---|---|---|---|---|---|
| Sensors | | | | | | | | |
| **PF** | 1.53 | 3.02 | 3.36 | 4.62 | **1.4** | 2.42 | 3.06 | 4.25 |
| **DMAPF(1.1,1)** | 1.49 | 2.58 | 3.24 | 4.57 | **1.4** | 2.39 | 2.99 | **3.9** |
| **DMAPF(2,1)** | 1.34 | 2.17 | 2.75 | 3.63 | **1.4** | 2.36 | **2.94** | 4.15 |
| **DMAPF(4,1)** | 1.34 | 2.12 | 2.68 | 3.6 | **1.4** | **2.33** | 3.01 | 6.43 |
| **DMAPF(10,1)** | 1.34 | 2.08 | 2.63 | 3.79 | **1.4** | 2.41 | 4.35 | 12.18 |
| **CMAPF(1)** | 1.36 | 2.11 | 2.64 | 3.65 | 21.96 | 22.22 | 22.5 | 22.68 |
| **CMAPF(0.1)** | **1.32** | **2.01** | **2.45** | **3.39** | 8.37 | 19.41 | 21.45 | 22.17 |
| **CMAPF(0.01)** | 1.41 | 2.3 | 2.81 | 3.84 | 1.64 | 3.8 | 6.32 | 11.92 |
| **CMAPF(0.001)** | 1.51 | 2.56 | 3.25 | 4.44 | 1.42 | 2.42 | 3.09 | 4.15 |

# 5. Conclusion

The performance of the MAPF methods depends on several factors, including sensor reliability, the dominance of map-awareness in weight calculations, particle cloud size, and distance from the road. Depending on the data itself, map-aware preference ratios should be chosen carefully. Higher sensor precision reduces the reliance on map-awareness, which is beneficial in scenarios where map data is less relevant. In contrast, low sensor reliability combined with strong map-awareness leads to a higher map-awareness weight ratio, significantly improving filtering accuracy. However, in cases where the tracked object deviates substantially from the road, excessive biasing toward map data in CMAPF can degrade performance, suggesting that adaptive switching between different map-awareness and traditional filters is crucial in real-world applications.

Future research should test MAPFs across diverse environments and sensor conditions to assess its generalizability. Additionally, adaptive parameter tuning methods, potentially informed by historical data, could further enhance MAPF's performance in various tracking challenges, allowing for more robust application across different environments.

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# CYBERRESILIENCE METRICS TO ENHANCE BUSINESS CONTINUITY

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Cybersecurity is a dynamic, human-made environment where information, processes, and technologies converge, making cyber resilience essential for sustainable economic development. Cyber incidents undermine national security, economic stability, and digital transformation, underscoring the need to strengthen cyber capacity globally, particularly among SMEs, where each participant's responsibility in the cyber domain is critical. Cybersecurity is transdisciplinary because it intersects various fields, including technology, economics, sociology, and law. Collaboration among experts from these domains is required to effectively address complex challenges related to risk management, regulatory compliance, and the socio-economic impact of cyber incidents.

This research introduces a cyber resilience metrics framework that consolidates security controls by functional areas, aligns them with incident lifecycle stages, and clarifies each stage's purpose and tasks. Emphasising continuous testing and proactive updates, the framework makes compliance in the evolving cybersecurity landscape mandatory. Developed as part of a PhD thesis, this research offers a practical approach to implementing and validating a comprehensive set of cybersecurity measures. Expert validation confirms that these metrics promote compliance, competitiveness, and effective risk mitigation within a cost-effective framework. Simulated cyber exercises and the analytic hierarchy process (AHP) have demonstrated the framework's practicality. The European Union's recent cyber resilience regulations focused on critical infrastructure (NIS2, 2022; DORA, 2022; RCE, 2022), and the financial sector mandates regular testing of business continuity plans and annual assessments of cyber capabilities and resilience. Given SMEs' pivotal role in the EU economy, especially in Latvia, Lithuania, and Estonia, these regulations further emphasise SMEs' essential responsibilities in maintaining regional cyber resilience.

## 1. Introduction

"Instead of thinking of cybersecurity as a technical problem + humans, researchers suggest cybersecurity should be conceptualised as a social problem + technology." (Cavelty et al., 2023). Cyber resilience frameworks are now essential to securing business continuity within an increasingly complex cybersecurity landscape. These frameworks help organisations prepare for, respond to, and recover from cyber incidents, protecting economic stability and supporting digital transformation. Cybersecurity incidents threaten national security, economy, and health, making resilience critical for sustainable development.

Governments and regulatory bodies, particularly within the European Union, have prioritised strengthening cyber capacity to address these challenges. EU regulations now mandate regular testing of business continuity plans and annual assessments of cyber resilience, particularly for critical infrastructure and financial sectors that require robust protection against cyber threats.

An essential advancement is the development of metrics-driven frameworks, which offer organisations a structured method to assess cybersecurity readiness. Metrics that track risk identification, mitigation, and management accurately measure an organisation's preparedness to protect critical infrastructure services.

Crisis simulations demonstrate the value of these frameworks, showing how metrics-driven approaches support rapid, goal-oriented responses to incidents. Metrics on business continuity and data security further support operational stability, reinforcing long-term resilience.

Maintaining business continuity is crucial for organisations to operate during and after disruptions in a competitive landscape. This requires strategic preparation to uphold critical functions amid security breaches or disasters. A business continuity plan (BCP) outlines the strategies and resources needed for swift recovery, including disaster recovery efforts to restore systems and data. As cyber resilience evolves, particularly for SMEs, these frameworks provide a pragmatic approach to compliance and support competitiveness by reducing cybersecurity risks cost-effectively.

## 2. Research design

The research article, part of theoretical and secondary data analysis, adopts an integrated methodology combining qualitative and quantitative approaches to achieve a prototype. Qualitative methods, including expert interviews, observations, and qualitative data analysis, drive a deep exploration of the research topic, uncovering connections and motivations related to the subject matter (Creswell and Poth, 2018; Patton, 2015). Additionally, quantitative methods—such as experiments and statistical analyses—provide insights into the prevalence and, according to Babbie and Fowler's research results, provide relationships between the phenomena studied (Babbie, 2017; Fowler, 2014).

Preparation tasks such as discussion guidelines and prepared transcripts from focus group discussions were validated. The data collected during the pilot interviews and expert opinions go under coding procedures and normalisation workflows to prepare for further analysis. Subsequently, quantitative data processing involved correlation and cluster analyses, enabling a thorough examination of the data.

The cybersecurity controls under research criteria were classified, evaluated, and analysed within specific consolidation indicators. Notably, only a small subset of these controls is directly attributable to cyber resilience. The organisation distinguishes 14 functional domains in cybersecurity, and only four are linked to cyber resilience. The study also outlines three phases of the cyber incident lifecycle—before, during, and after an incident—to structure the measurements of cyber resilience across different stages of decision-making in incident response and post-incident evaluation. The detailed view of incident handling and response timeline shows core milestones (marked as a start) where metrics-driven approaches are essential.

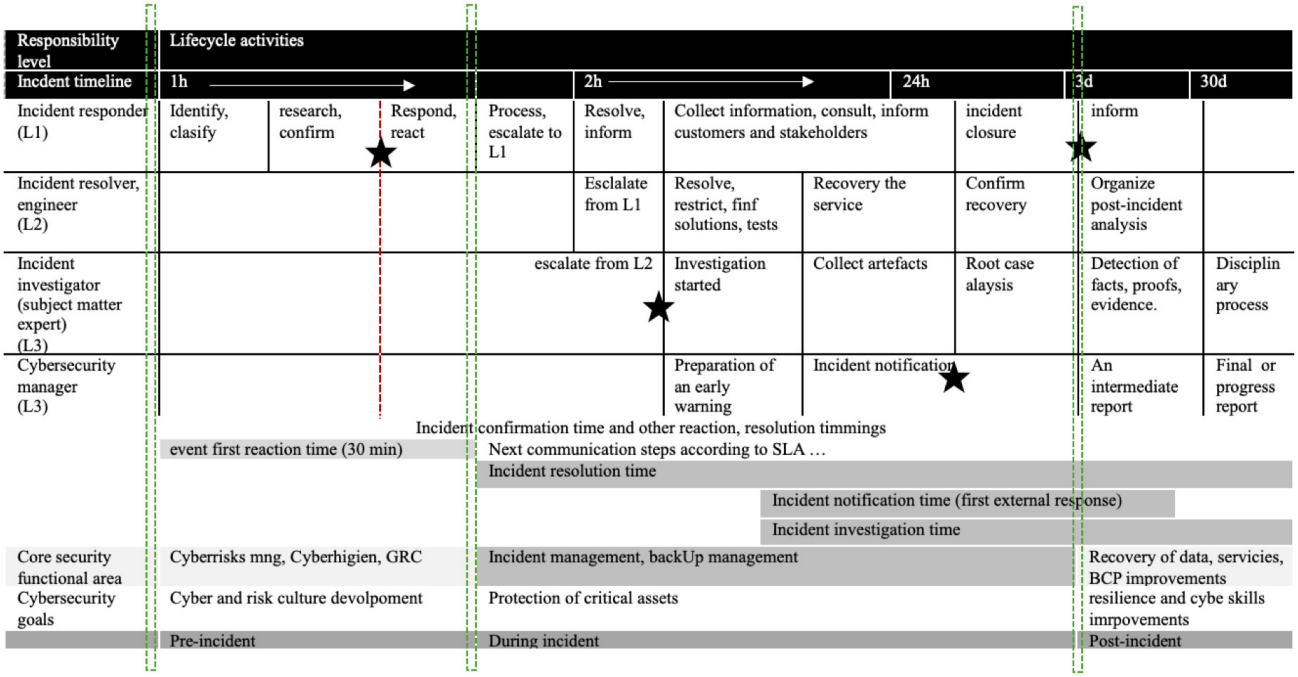


*Figure 1: incident timeline dimensions and workflows*

The incident timeline model (Figure 1) shows the data triangulation path of literature, standard reviews, and result integration (set of criteria) to create and design a KK framework pilot for expert validation, as well as to simulate business continuity situations. This model includes several functional areas of the organisation's resilience: preventive control, reasonable action, performance optimisation and adaptive innovation.

Strengthening the components' resilience in the organisation's dimensions characterises these functional areas. Different criteria and characteristics in the model include protective measures correlated with regulatory enactments, standard requirements, and business and regulatory requirements. Usually, this type of compliance requirement in the organisation's ecosystem is integrated with security controls. Thus, security controls have classification, evaluations, and performance indicators. The phase of the post-incident analysis is crucial for the assessment of the results. It helps to respond to the organisation's essential elements of resilience and cyber skills—whether everything is done to prevent the incident from happening again—and identifies the weaknesses of cyber resilience functional domains. The optimal set of metric framework measurements is based on the results of the quasi-experiment in the second and third incident management lifecycle phases. At the end of the research, the principal results are formulated, and proposals for implementing the metric framework are made.

# 3. Cyberresilience

Cyberresilience has emerged as a distinct concept in scientific literature since 2015 (Björck et al., 2015). It is closely related to cyber maturity, the capacity to anticipate, withstand, recover from, and adapt to adverse digital resource conditions (NIST, 2020). Resilience includes adapting and responding positively to significant adversity, a dynamic process articulated in earlier social science literature (Garmezy, 1990; Rutter, 1990).

Stakeholder awareness in cybersecurity management is crucial for establishing meaningful performance indicators (Cano, 2019). During the decade, annual threat reports from research organisations consistently highlight cybersecurity risks (Allianz, 2019, 2025; Mitre, 2018; Cambridge Centre for Risk Studies, 2018). While fundamental security controls are vital, human actions—such as decision-making and adapting security solutions to unexpected attacks—significantly enhance cyber resilience (Cavelty et al., 2023).

Quantitative risk assessment techniques enable accurate estimations of total losses from cyber incidents, aiding in reassessing the value of information resources and necessary investments in risk mitigation. Information valuation is pivotal in formulating an adequate information security budget, necessitating an inventory of organisational resources to underpin a sound digital strategy. This strategy must ensure that the cost of protection does not exceed the value of the information being safeguarded.

Despite differing opinions on a unified metric formula, it is acknowledged that security metrics must be characteristics of several elements that require interpretation. These metrics are essential for business management and security teams to facilitate investment decision-making and compliance with risk appetite. Ukrainian researchers emphasise that the effectiveness of security metrics is influenced by business process functionality, resource classification, and the security goals outlined in company policies (Yevseiev et al., 2022).

# 4. Expert interviews

The selection and categorisation of information security standards are crucial in assessing an organisation's cyber resilience. Experts utilise various standards to identify critical security controls that contribute to determining the level of resilience. To establish a coherent framework, reaching a consensus on specific security categories, sub-group classifications, and additional units for evaluation is essential. This process also involves defining influence criteria and discussing implementation or maintenance costs to validate the experts' choices and the metrics used.

The expert interviews aimed to assess a list of cybersecurity metrics through both qualitative and quantitative methods. Based on expert recommendations, the interview questions were refined into a structured questionnaire that facilitated the selection of experts. Ultimately, eleven experts were chosen for their in-

sights. The summary of their backgrounds revealed that 50 % of the experts operate within the European Union, 30 % work globally, and 20 % are based in Latvia. Additionally, 40 % are risk and compliance executives, 40 % serve as security advisors and analysts, and 20 % hold IT management positions.

The selection process for experts included inquiries about their cybersecurity certifications and the maturity level of their organisation's cybersecurity practices. The minimum acceptance criteria required that the primary cybersecurity control be established in their organisations and that their cybersecurity maturity process be nearing level two, with 67 % of responses indicating a third-level maturity. Experts were also expected to possess practical experience in implementing security measurement programs and hold recognised professional certifications, such as CISA, CISM, or CRisk.

The arguments for the selection process were the following. Diverse Expertise: Including experts from various sectors (EU, global, and Latvian) ensures a broad perspective on cybersecurity metrics, enhancing the robustness of the findings (Shay et al., 2020).

Focused Backgrounds: Selecting professionals with roles in risk compliance, security advisory, and IT management provides insights from multiple angles of cybersecurity, which is crucial for understanding comprehensive security measures. Certifications as a Benchmark: Requiring recognised professional certifications establishes a baseline of competence among experts, ensuring that participants possess relevant knowledge and experience in cybersecurity. Maturity Level Assessment: Setting maturity level criteria for organisations gauges the current state of cybersecurity practices and aligns expert insights with industry standards, facilitating a more accurate assessment of resilience.

## 4.1. Analysis of the Analytic Hierarchy Process (AHP) for Cybersecurity Metrics

The Analytic Hierarchy Process (AHP) method has been recognised for its effectiveness in decision-making, particularly in complex scenarios (Mardani et al., 2015). AHP allows decision-makers to evaluate contradictory goals and alternatives, especially in cases where risk modelling, uncertainty, or sensitivity analysis is involved. This quantitative data processing procedure incorporates expert consensus to weigh criteria, focusing on synthesising information security metrics rather than merely optimising them. Industry security experts evaluated security controls based on three primary criteria: impact on risk portfolio, internal cost of the company, and level of maintenance competencies. The results are summarised in the table below.

*Table 1: the criterion's summary*

| Criterion | Measurement | Value |
|---|---|---|
| Impact on Risk Portfolio | M7: Third-party resources identified, monitored, controlled, and supported. | High |
| | M8: Incidents recorded as non-compliance identified and notified. | High |
| | M11: Incidents of lost or stolen user equipment (annual cases known). | High |
| Internal Cost of the Company | M5: Information resources identified, responsible parties defined, and policies implemented. | Low |
| | M9: Incidents recorded as system breaks due to cyber-attacks identified. | Low |
| | M17: Company's outsourced risk rating evaluated; outsourcing providers classified. | Low |
| Level of Maintenance Competencies | M5: Information resources identified, responsible parties defined, and policies implemented. | Low |
| | M9: Incidents recorded as system breaks due to cyber-attacks identified. | Low |
| | M17: Company's outsourced risk rating evaluated; outsourcing providers classified. | Low |

According to experts, metrics related to incident response capabilities are prioritised over the annual count of lost devices. Additionally, metrics concerning compliance with outsourcing contracts and resource health

checks significantly influence the organisation's overall security posture. Thus, measurements that focus on identifying, classifying, and monitoring information resources are crucial.

Reliability Assessment: Cronbach's alpha measures internal consistency reliability, assessing the credibility of the item set. The dataset underwent preparation through cleaning and normalisation to analyse cyber-resilience metrics. The expert evaluations were converted to a Likert scale using online calculation tools.

Cronbach's alpha results indicate varying levels of internal consistency among the measurements:

Measurement M5: Information resources are identified, responsible parties are defined, and policies are implemented. Cronbach's alpha: 0.65 Measurement; M9: Incidents recorded as system breaks due to cyber-attacks identified. Cronbach's alpha: 0.87 Measurement; M16: Deliberate vulnerabilities in information systems. Cronbach's alpha: 0.80. Overall, the alpha coefficient for the six categories in the measurement framework ranged from 0.71 to 0.87, demonstrating sufficient reliability for the framework used in this study.

The AHP method is a robust framework for assessing cybersecurity metrics, balancing expert opinions on the importance of various measurements. The findings underscore the need for organisations to prioritise incident response capabilities and adequately manage information resources to enhance overall cybersecurity resilience.

## 4.2. Cybersecurity exercise

After expert evaluations, a cybersecurity exercise was conducted in five stages, according to (Vykopal et al., 2017). The accuracy of the simulated environment directly impacts implementation costs, but such exercises effectively reduce the cybersecurity competence gap (Furnell et al., 2017). Participants in scenario exercises spent 2-3 h per scenario, with groups of 60 participants that included 50-80 % cyber specialists. Their overall self-assessment results were deemed average. During the exercise, participants were informed about the conditions and rules, allowing for adjustments based on their questions. Effective questioning facilitated informed, risk-based decision-making. Participants were tasked with calculating operational risks using prepared policies and templates. The types and content of information requests during the scenarios were recorded and analysed. Post-exercise, data was coded and categorised into metrics, normalised for quantitative analysis, which included correlation and cluster analysis. A high correlation coefficient with significant P-values indicated a strong relationship between variables (Figure 2), suggesting they move together reliably. This correlation is essential in statistical hypothesis testing, assessing the significance of observed data (Field, 2013; Hair et al., 2010).

Testing hypotheses through controlled experiments is essential in cybersecurity research, providing empirical evidence of causality (Shadish et al., 2002). This approach allows researchers to isolate critical variables, such as response times and information flow, to produce precise, actionable insights into incident response and team effectiveness (Johnson et al., 2011). Scenario-based exercises and simulations replicate real-world conditions, enhancing the reliability of hypotheses on skills, response efficiency, and decision-making in high-stakes cyber environments (Lazar et al., 2017).

Due to the evolving nature of threats, experiments are crucial in cybersecurity. They facilitate assessments of team coordination, communication pathways, and automation needs under controlled, stress-inducing conditions (Rogers et al., 2018). By leveraging quantitative and qualitative data, experimental studies support the development of refined, reliable metrics and frameworks for cyber resilience.

| r | $r^2$ | Slope | Y Intercept | Std. Err. of Estimate |
|---|---|---|---|---|
| 0.9685 | 0.938 | 8.527132 | -2.054264 | 0.2784 |

| t | df | P | one-tailed | <.0001 |
|---|---|---|---|---|
| 11 | 8 | | two-tailed | <.0001 |

*0.95 and 0.99 Confidence Intervals for rho*

| | Lower Limit | Upper Limit |
|---|---|---|
| 0.95 | 0.869 | 0.992 |
| 0.99 | 0.799 | 0.995 |

*0.95 and 0.99 Confidence Intervals for the Slope of the Regression*

| | Lower Limit | Upper Limit |
|---|---|---|
| 0.95 | 6.7364 | 10.3178 |
| 0.99 | 5.9225 | 11.1318 |

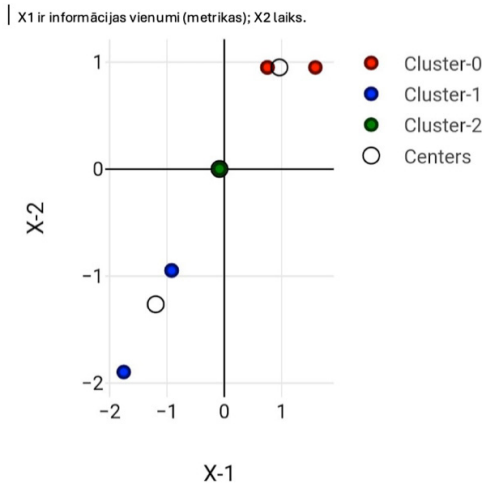


*Figure 2: Results of a correlation coefficient; cluster analysis of metrics (x1-information, x-2 time)*

There is a significant correlation between the outcomes of cyber incident resolution, precisely the time taken, and the volume of information requested, as illustrated by the metrics in Figure 2. Scenario-based exercises and similar testing methodologies effectively demonstrate the rapid development of cybersecurity skills. Participants acknowledged that incident investigation and post-incident analysis are instrumental in identifying the factors contributing to ongoing incidents. These analyses also highlight opportunities for improving individual and team performance, enhancing response capacity, and assessing preparedness and competency levels. Such types of analyses reveal communication shortcomings and gaps in information that hinder decision-making—a disadvantage noted during focus group discussions on security metrics. Additionally, these insights point to potential avenues for process automation. Focus group discussions identified several security risks that are consolidated in Table 2.

*Table 2: consolidation of risk identified after focus group discussions*

| Categories of the cybersecurity controls | Improvement areas |
|---|---|
| Incident handling | Need to improve the post-incident analysis, gather details and full information, separate investigating, data processing, handling and reporting procedures in three expert lines. |
| Cybersecurity performance | Need to improve the reporting channels pf the actual security-related metrics, indicators, and start to implement a continuous metrics program |
| BCP | Need to improve and diversification of the Business continuity planning, testing methods, such as table-top, simulations etc. |
| Crisis communication | Need to develop crisis communication plans, protocols, guidelines etc., granularly re-assess current communication channels and tools |
| Cyber skill inventory | Need to develop the expert knowledge of incident response, re-assess current cyber skills, competency |
| Decision making, escalation trees | Need to develop decision-making skills in crisis, implement documentation guidelines engaging C-level management |

Testing diverse plans requires substantial resources and time but offers significant added value. Focus group results indicate that scenario-based cybersecurity exercises are underutilised. Such testing is vital for enhancing an organisation's cybersecurity maturity and ensuring business continuity during crises. Multiple testing methods confirm the effectiveness of the plans across various situations, enabling staff to maintain the organisation's cyber resilience. Cyber resilience testing focusing on employee decision-making is crucial for training staff, ensuring they understand their roles and adhere to established procedures. Continuous testing is often linked to information systems and infrastructure, allowing organisations to evaluate the efficiency of systems, data recovery, and resistance to cyber-attacks and emergencies. Relying on a single test may fail to uncover flaws, highlighting the necessity for ongoing performance improvements. The KK framework enhances security controls by categorising them into functional areas, linking them to the stages of the incident lifecycle, and clarifying the purpose and tasks associated with each stage (Jones et al., 2020; Smith, 2021). This structured approach facilitates continuous adaptation to evolving cybersecurity challenges.

# 5. Conclusions

Cyber resilience is a fundamental aspect of cybersecurity, showcasing an organisation's capability to manage crises effectively. The performance of cybersecurity teams, characterised by their collaboration, responsiveness, and information sharing, is essential for successful crisis management. Organisations must demonstrate the ability to adapt and endure under challenging external conditions, often leading to innovative solutions despite resource constraints.

**Development Levels:** Cyber resilience evolves progressively across three key levels: people, processes, and technologies. Each level plays a critical role in enhancing overall security. Control Classification: Classifying cybersecurity controls is crucial for identifying, aligning, and prioritising protective measures based on resource classifications, information value, and risk assessments. This classification is necessary for complying with regulatory standards and guidelines

**Assessment Awareness:** Enhancing awareness of cybersecurity metrics and fostering a culture of diversity, usability, and applicability are imperative for implementing effective measures. Different types of assessments, including security control evaluations and maturity assessments, are integral to understanding the effectiveness of cybersecurity strategies.

**SME Challenges:** Many small and medium-sized enterprises (SMEs) fail to implement essential security controls due to a lack of understanding, expertise, and resources. This gap hampers their ability to identify where to invest effectively in cybersecurity.

An automated and continuous cyber resilience assessment offers a more accurate perspective on cybersecurity across functional areas. Using a unified methodology enhances the reliability of comparative data.

The KK framework proposed by the author outlines six essential categories of security controls, validated through expert evaluations and regulatory analyses. Regular measurement of cyber resilience is crucial, with security metrics articulated in a prepared template encompassing categories, processes, metric types, sources of information, and measurement significance. The summarised risk list is directed at the implementers of the metrics program. Generally, the information security manager necessitates additional time, technical resources, and competencies for effective implementation.

In conclusion, the analysis emphasises that organisations must prioritise developing a structured approach to cybersecurity through systematic assessments, practical training, and robust resource allocation.

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