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Waste-based fuels as part of sustainable mobility

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Abstract

One of the main challenges for sustainable and new energy-based mobility is the development of alternative fuels, particularly those produced from waste. This paper aims to review the scientific literature on waste-based fuels and identify key technological, economic, and environmental trends. The paper presents a two-stage methodology: first, a quantitative analysis was conducted using the Scopus database. A qualitative evaluation of relevant studies follows it. The results of the analysis indicate that research primarily focuses on the pyrolysis of plastic waste and high-calorific fractions, as well as the biorefinery concept. In contrast, catalytic and thermochemical processes are the primary focus of the technological approaches. Waste-based fuels offer savings of up to 43% compared to fossil fuels and a favourable emissions profile; however, economic viability and regulatory frameworks remain significant challenges. The study concludes that widespread adoption requires an integrated approach that combines technological innovation, economic incentives, and life cycle assessments.

Keywords:
waste-based fuels; circular economy; biorefinery pyrolysis; sustainable mobility

1. Introduction

One of the greatest technological and societal challenges of the third millennium is the question of sustainable mobility. Since the global division of labour is one of the foundations of civilisation, people and goods move across countries and continents, which requires significant energy consumption and, in most cases, contributes to environmental pollution. The search for solutions has been ongoing for a long time, and economic instruments can significantly influence whether a particular technology is promoted or hindered. A good example of this is the European Union and electromobility, whose regulatory instruments have enabled the proliferation of electric cars (Zoldy et al., 2022). However, it is clear that electromobility, with its current technological solutions, cannot replace traditional mobility based on internal combustion engines. Another global trend present in all mobility sectors is data-driven transport, also known as cognitive mobility (Zoldy et al., 2024). Numerous complementary research projects have been initiated and are ongoing to develop sustainable mobility solutions. One research approach involves liquid fuels from waste. The use of waste fuels is of paramount importance for sustainability and environmental protection for several reasons. The development and application of waste fuels enable the utilisation of materials generated by human activities, thereby reducing the amount of waste that ends up in landfills (Torok et al., 2014).

The investigation of waste as a liquid fuel feedstock is closely linked to sustainability goals, specifically the recycling and utilisation of materials that arise as byproducts or losses in the original production process (Németh, 2021). Fuels produced from waste fulfil the requirements of the circular economy system, as recycling materials, including fuel production from waste, is generally less energy-intensive than the extraction, transportation, and processing of raw materials. This reduces greenhouse gas emissions and the overall environmental impact. Waste-based fuels can represent a solution for the transition from a linear to a circular value chain. Instead of simply

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disposing of waste in landfills or incinerators, which often only shifts the problem, waste is used to produce liquid fuel. Waste is thus not an end product, but a new resource.

The financial aspects of the circular economy also have a huge impact on use. One source highlights the importance of a transparent regulatory environment that promotes more efficient waste management and the development of corresponding technologies. The development and application of fuels from waste is also of central importance in this context, as it can create economic incentives for waste management and alternative energy sources. In the mobility sector, public funding programs play a particularly important role, as they can guide market development while taking environmental aspects into account (Szalmáné Csete et al., 2024). The Club of Rome's 1972 report, "The Limits to Growth" (Meadows et al., 1972), already warned about the unsustainability of unlimited growth, laying the foundation for today's circular economy and the demand for fuels derived from waste (Bourguignon, 2016).

This study aims to present and evaluate publications on the topic of fuel production from waste and to identify potential research directions through this analysis. A detailed evaluation and analysis follow the presentation of relevant studies.

2. Literature analysis

The overview of relevant sources was completed in two steps. First, a quantitative overview was conducted using the Scopus database. The focal points of the investigation were the feedstocks used and the processing technologies employed. In the second step, the selected papers were analysed more deeply.

The relevant sources were selected with the help of a SCOPUS query of "TITLE-ABS-KEY(waste AND recycl* AND fuel) AND PUBYEAR > 2010 AND PUBYEAR < 2026", which yielded a total of 7531 documents containing the keywords "waste", "fuel" and keywords starting with the stem "recycle" in either their title, abstract, or the keywords assigned to the publication either by the authors or by the publisher. The investigation was limited to papers published after 2010, with a focus on more recent works. The resulting data was exported to an ASCII file and processed using a simple Python script, which compared the contents of the article abstracts with a list of predefined keyword tokens. Prior to counting the number of papers that deal with each method and source in question, an additional filtering step was introduced: papers that did not explicitly contain "fuel" or "energy" in their abstracts were discarded, resulting in 6659 entries. The number of papers dealing with different waste sources was determined by looking for the tokens "agricultural waste", "sludge", "food waste", "plastic waste", and "tire".

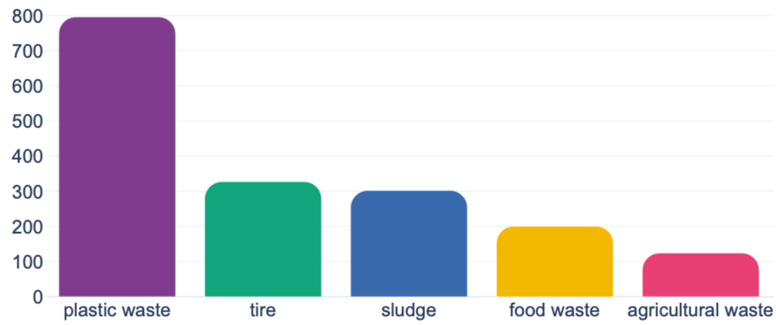

Figure 1. Count of papers by feedstock in the Scopus database from 2010 to 2025.

For the number of papers dealing with selected production methods, the following tokens were used: "thermochemical", "biochemical", "biological", and "catalytic". The authors would like to acknowledge the simplicity of this method and its resulting limitations, as this approach cannot account for variations in wording, only exact matches. Therefore, the sum of papers in separate categories will not be equal to the total number of papers involved in the analysis.

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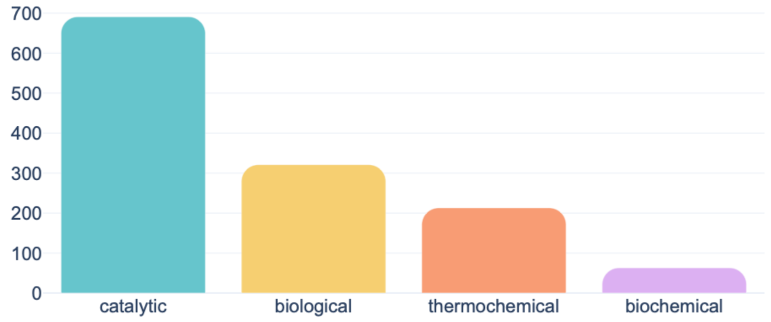

Figure 2. Count of papers by production process technology in the Scopus database from 2010 to 2025.

More sophisticated approaches involving Large Language Models would certainly lead to higher precision in categorising papers and determining the number of publications focusing on different methods and waste sources. Nevertheless, this simple method led to the realisation that most of the attention is focused on plastic waste as a source (Fig. 1), followed by end-of-life tires, sludge, and food waste, whereas agricultural waste as a source of fuel or energy production is less discussed. Regarding production methods, catalytic upgrading is the most popular technology (Fig. 2), followed by biological and thermochemical methods, with biochemical methods being of the least interest in the scientific community.

3. Literature review

To provide a deeper understanding of the technological, economic, and environmental dimensions of waste-based fuel research, this section critically examines selected studies that represent distinct milestones and thematic clusters within the broader literature. These papers were chosen because they introduced foundational concepts, proposed innovative technological pathways, or addressed practical challenges in scaling waste-derived fuels. The sequence of discussion follows a logical progression to illustrate the evolution of research on waste-based fuels. It begins with foundational studies that establish the broader context of sustainability and energy, highlighting the global imperative for clean, affordable, and reliable energy, as well as the conceptual frameworks that underpin the transition toward renewable sources. Building on this foundation, the review moves to early investigations into biomass and biofuel production, which introduced key technological pathways such as lignocellulosic conversion and ethanol synthesis, while addressing challenges related to cost and resource competition. The next stage focuses on integrated biorefinery concepts and circular economy approaches, emphasising strategies that maximise resource efficiency by producing not only fuels but also high-value chemicals from diverse waste streams. Following this, attention shifts to specific technological solutions, including thermocatalytic pyrolysis of plastics, hydrogenation of waste fractions, and the development of slurry fuels, each offering distinct advantages and facing unique technical and economic barriers. Finally, the section concludes with applied and experimental studies that validate these concepts through combustion simulations and engine performance tests, providing empirical evidence of feasibility and environmental benefits. This structured approach enables readers to trace the trajectory of research from theoretical foundations to practical applications, revealing both continuity and innovation in the pursuit of sustainable mobility.

Several studies provide a general overview of fuel production from waste. For example, Chu and Majumdar (2012) set the strategic context for why waste-based fuels are important. They argue that the world needs a “new industrial revolution” to achieve affordable, accessible, and sustainable energy, emphasising the urgency of decarbonising transportation fuels. The paper highlights biofuels – particularly those derived from lignocellulosic biomass and waste streams – as critical alternatives to petroleum-based fuels. It also frames the challenges of scalability, infrastructure, and life-cycle emissions, noting that advanced biofuels can reduce greenhouse gas emissions by over 60% compared to fossil fuels when properly managed. By situating biofuels within broader energy policy and technology pathways, this article provides a macro-level rationale for investing in waste-derived fuels as part of a diversified clean energy portfolio. In the 21st century, energy use must be sustainable. Solar energy, hydroelectric power, and the development of microorganisms for biofuel production are examples of

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alternative energy sources. This study situates these options within a broader context, linking the areas of energy transport and production, and provides an overview of the current energy landscape, as well as the lines of research and development that can lead to a sustainable and secure future.

Huber et al. (2006) conducted a comprehensive review to understand the technical feasibility of converting waste biomass into liquid fuels. It details the chemistry and engineering of major conversion routes – gasification to syngas, pyrolysis to bio-oil, hydrolysis to sugars, and upgrading processes such as hydrodeoxygenation and zeolite catalysis. The paper also analyses process thermal efficiencies, life-cycle considerations, and economic factors, making it clear that waste biomass is the only renewable source of organic carbon suitable for producing liquid fuels on a large scale. Importantly, it introduces the concept of integrated biorefineries and evaluates emerging catalytic strategies for improving yields and reducing costs. This work remains a key reference for researchers developing waste-based fuel technologies because it bridges fundamental chemistry with industrial process design and sustainability metrics. They examined methods and future possibilities for fuel production from biomass. Topics covered include the chemical composition and growth rate of biomass, gasification, synthesis gas utilisation, bio-oil production and refining, monomer production, sugar-to-fuel conversion, conversion of non-sugar monomers from lignocellulose, and triglyceride conversion, as well as ethical considerations.

In the early stages of renewable fuel research, agricultural waste was primarily considered a potential feedstock for biofuel production. In the case of ethanol, producing fuels from byproducts could resolve the competition between food supply and biofuel production (Emőd et al., 2005). Sun and Cheng (2002) also demonstrate that lignocellulosic biomass can be utilised for the production of ethanol, a promising alternative energy source due to the limited availability of oil reserves. The conversion process involves two main steps: the hydrolysis of cellulose to produce reducing sugars, and the subsequent fermentation of these sugars into ethanol. Costs are currently high, mainly due to the low hydrolysis yield and the associated expenses. Research focuses on removing lignin and hemicellulose, optimising the enzymes, and simultaneously saccharifying and fermenting to increase yield.

Shanthi Sravan et al. (in press) are investigating the potential of waste-derived fuels and chemicals in the context of bioeconomy, highlighting the concept of the biorefinery. This comprehensive review summarises research on the use of biomass waste and other waste streams in biorefineries for the production of both fuels and valuable chemicals, thus promoting a circular economy approach. It demonstrates how waste can be a source of more valuable products than simple fuels, thereby maximising resource utilisation and economic benefits.

Moving on to more specialised technologies, Misra et al. (2025) specifically address the pyrolysis process for converting plastic waste into fuel oil, describing in detail the technological aspects and the quality of the resulting fuel. This study analyses the various pyrolysis techniques applied to different types of plastic waste, evaluates factors such as temperature, residence time, and catalysts, and assesses the composition and properties of the resulting fuel oil. Polystyrene was found to be the most promising candidate for producing fuel oil through pyrolysis.

Another technology is described by Tóth, Holló, and Hancsók (2020). Their study demonstrates that waste fractions generated during the refining of vegetable oils and animal fats, as well as in paper production, can be converted into an alternative diesel fuel through several steps. In their research work, several waste fractions were hydrogenated with raw gas oil, and the reactions and product quality were investigated. The fuel produced under optimal conditions demonstrated better application performance compared to conventional diesel, thus offering a more environmentally friendly and lower-emission solution.

It is not only selectively collected waste that may serve as the basis for fuel production. According to a study by Vershinina, Shlegel, and Strizhak (2020), sewage sludge fuels derived from waste can have favourable energy properties (calorific value, ignition delay, and combustion temperature) and a low environmental impact (low CO_2, NO_x, and SO_x emissions). The mixtures were produced from wood, agricultural, and household waste, as well as wastewater, petrochemical waste, and heavy oil additives. The results indicate that the use of coal and oil can be reduced by up to 43% with such mixtures.

While the above-discussed articles introduced technologies to produce fuels from waste, other studies tested the properties of the resulting fuels. Kondor and colleagues presented their results on waste-based fuels in two studies

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(Kondor and Zoldy, 2020; Kondor et al., 2021). In the article "Combustion Simulation Studies with Waste-Based Fuels", the aim was to investigate the combustion properties of waste-based fuels using simulation. The methodology involved the use of CFD (Computational Fluid Dynamics) simulations or other combustion modelling software to simulate the combustion process of fuels derived from waste materials, focusing on the combustion behaviour, efficiency, and potential emissions of these fuels to support their practical application. As presented in the other study, Kondor et al. (2021) aimed to experimentally evaluate the performance and emission characteristics of a compression-ignition engine using fuel mixtures of waste tire pyrolysis oil and diesel. The methodology included engine bench tests, in which the engine was operated with different mixtures of pyrolysis oil and diesel. The results provided empirical data on the suitability of tyre pyrolysis oil as a diesel fuel additive, highlighting its performance and environmental compatibility, and assessing its potential as a viable alternative fuel.

4. Evaluation of the literature

A summary of the literature review is given in Table 1. Studies have shown that a wide range of waste-based raw materials exists. The main goal of research on waste-based fuels is the development of diesel fuel additives; however, in some cases, gasoline substitutes are also being investigated.

Table 1. Waste-derived fuels and bio-based alternatives – literature review

Authors and Year	Focus	Waste Stream / Feedstock	Technology / Approach	Key Findings
Sravan et al. (in press)	Biorefinery concept, circular economy	Mixed waste streams, biomass	Integrated biorefinery systems	Waste can be a source of multiple valuable products (fuels + chemicals), and resource maximisation.
Misra et al. (2025)	Pyrolysis of plastic waste for fuel oil production	Plastic waste	Pyrolysis (temperature, catalyst, residence time)	Fuel oil quality and composition, potential of pyrolysis
Chu & Majumdar (2012)	Future of sustainable energy	Renewable energy sources	Solar, hydro, biofuels	Sustainability framework, R&D directions
Huber et al. (2006)	Biomass-based transportation fuels	Biomass	Gasification, syngas utilisation, bio-oil, sugar conversion	Current methods and future possibilities
Sun & Cheng (2002)	Hydrolysis of lignocellulose for ethanol production	Lignocellulose	Hydrolysis + fermentation	High cost, yield issues, enzyme optimisation
Vershinina et al. (2020)	Waste-based slurry fuels	Wood, agricultural, and household waste	Wastewater + petrochemical additives	Up to 43% fossil fuel savings, favourable energy and environmental characteristics
Tóth et al. (2020)	Hydrogenation of waste fractions for diesel	Vegetable oil, animal fat, paper waste	Hydrogenation with raw gas oil	High-quality diesel, better performance, lower emissions

The studies in the table demonstrate that research on waste-derived fuels and bio-based alternatives is progressing in various directions and is increasingly aligning with the circular economy and sustainability paradigm. Three main focus points can be identified:

1. Integrated approach and the role of biorefineries – Sravan et al. emphasise the concept of the biorefinery, which produces not only fuels but also valuable chemicals from waste. This approach is essential for increasing economic feasibility and resource efficiency.

2. Technological diversity and challenges – Misra et al. point out that there is no overall solution to integrate waste streams based on their heterogeneity. Fuels with high caloric value and waste-based pyrolysis streams seem promising, but significant technological and economic challenges exist for industrial-scale applications. Catalysts, temperature parameters, and process optimisation are key factors.

3. Sustainability and environmental benefits – It has been clearly demonstrated that waste-based fuels can not only replace fossil fuels but also contribute to more favourable emission profiles.

5. Conclusions

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To summarise the study, research on waste-based fuels is a key area for sustainable mobility and energy transition. Based on the literature review, three main focus points can be identified. The first is the integrated biorefinery approach, in which waste is utilised not only as a fuel but also for the production of chemicals, thereby enhancing resource efficiency and economic benefits. The second focus point is the technological diversity and related challenges: pyrolysis, hydrogenation, and fermentation are promising technologies; however, heterogeneous waste streams and high investment costs may hinder their industrial-scale application. The third focus point concerns the sustainability benefits: waste-based fuels offer significant savings in fossil fuels and result in a more favourable emission profile, thereby contributing to the achievement of circular economy goals.

Research gaps in this field include the lack of economic viability, inadequate regulatory frameworks and the lack of life cycle assessments. Future research should take an integrated approach that combines technological innovation, economic incentives and quantification of environmental impacts. From a practical perspective, waste-based fuels have the potential not only to replace fossil fuels but also to contribute to waste reduction and energy security. However, their widespread adoption requires concerted efforts from industry, regulators and research institutions.

Acknowledgement

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Technology, people, and management working together: A new way for sustainable airport operations

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Abstract
This paper revisits the Technology–People–Management (TPM) framework for sustainable airport operations and strengthens its scientific grounding through a clearer theoretical foundation, transparent bibliometric methodology, and policy-oriented interpretation. A systematic review of fifty-one peer-reviewed articles published between 2010 and 2025 is complemented by keyword co-occurrence analysis to elucidate interdependencies among technology, human factors, and managerial practices. The study interprets these findings through socio-technical systems theory and innovation diffusion perspectives, and aligns them with strategic aviation roadmaps, including the ICAO Global Air Navigation Plan and the SESAR ATM Master Plan. Methodological rigor is enhanced by explicit criteria for keyword normalization, clustering parameters, and robustness checks, while discussion moves beyond description to analyze causal mechanisms that connect the three TPM components. The paper translates results into practical implications for regulators, air navigation service providers, and technology developers, and proposes a research agenda to address underexplored areas such as human–AI teaming, real-time machine learning in operations, and governance for data interoperability.

Keywords
Sustainable Airport Operations, Technology–People–Management (TPM) Framework, Cognitive Sustainability, Airport Ground Handling, Human Factors and Training

1. Introduction

Airports operate within increasingly complex environments where safety, efficiency, and environmental performance must be achieved concurrently. Prior research has often examined technology, human factors, or management in isolation, which obscures the interdependencies that shape operational outcomes. This paper advances the Technology–People–Management (TPM) framework by integrating established theoretical lenses, clarifying bibliometric procedures, and articulating how technology, people, and management interact to produce sustainable performance. The contribution is threefold: first, the study formalizes the conceptual underpinnings of TPM within socio-technical systems theory and innovation diffusion; second, it reports methodological choices and validation steps for the bibliometric analysis; third, it translates findings into actionable, policy-aligned implications for key stakeholders (Tam, Hoang, 2025; Tang et al., 2025).

In contrast, the rate of improvement in air traffic is also increasing, resulting in making a management organisation's management of an airport more complex and even more complex as time goes by. Research is typically performed either on air traffic control technology and/or air traffic control human factors or management systems (Weiszer et al., 2015; Padrón et al., 2016). There is also a tendency for researchers to focus their studies primarily on AI in the ground handling space (Jimenez et al., 2023; Ku, 2024; Yıldız et al., 2022) or on AI for training employees (Balk et al., 2011), but there is no clear picture of how these applications relate to managing the subcontractor (i.e. Air Traffic Control).

The present study addresses this gap using the Technology–People–Management (TPM) framework. TPM is applied to achieve performance enhancement of cognitive sustainability. Cognitive sustainability is the capacity of an organization to maintain the knowledge, health and decision making of its employees in a continuously evolving work place (Wu et al., 2026; Muecklich et al., 2023). Ultimately, the goal of the research is to ensure technology utilization and implementation enhance the work processes rather than adversely load the employees (Teperi and Leppänen, 2011; Dekker, 2004).

This research used an analytical methodology with the use of a specialized software ptogram – VOSviewer – as a research tool to assess literature relevant to the research focus (Bakır et al., 2022). The results show that there are very strong ties between technology, people and management; these three categories consistently prevailed in the 42 paper body of literature, as illustrated by Figure 1 below. The results indicate a close

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interrelationship of the concepts of technology, training and management; thus, the performance of the airports of Turkey and abroad is dependent upon managing both internal and external elements effectively (Güner and Seçkin Codal, 2022, Dönmez, 2024; Ertek, Taşcı, 2026).

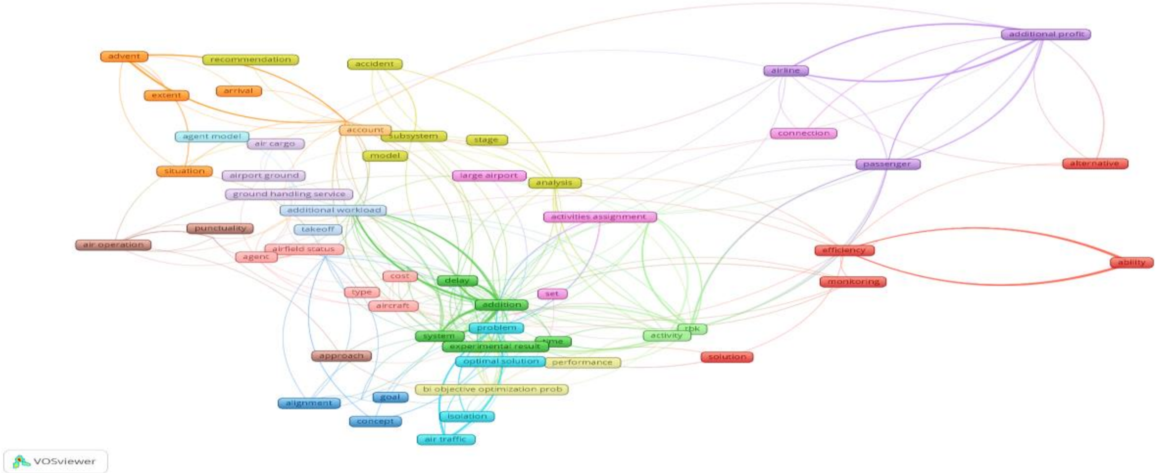

Figure 1. VOSviewer map showing the co-occurrence of keywords in the analyzed literature

Consequently, the following research question is the primary focus of this study: "How does integrating technology, people, and management simultaneously contribute to creating sustainable and supportive working environments for aviation personnel and the general public?"

> H_1: An integrated technology, people and management view (TPM) provides a better understanding of cognitive relatedness, compared to studying each of these components independently, with respect to sustainability, in the context of an airport's operation.

Airports operate within increasingly complex environments where safety, efficiency, and environmental performance must be achieved concurrently. Prior research has often examined technology, human factors, or management in isolation, which obscures the interdependencies that shape operational outcomes. This paper advances the TPM framework by integrating established theoretical lenses, clarifying bibliometric procedures, and articulating how technology, people, and management interact to produce sustainable performance. The contribution is threefold: first, the study formalizes the conceptual underpinnings of TPM within socio-technical systems theory and innovation diffusion; second, it reports methodological choices and validation steps for the bibliometric analysis; third, it translates findings into actionable, policy-aligned implications for key stakeholders.

2. Methods

The empirical basis of this synthesis is a systematic review of 42 journal articles published between 2010 and 2025 that address at least one dimension of technology, people, or management in airport contexts. All articles are given in the Reference list. Articles were retrieved primarily from ScienceDirect and Web of Science and screened for relevance to the TPM framework and cognitive sustainability. Keyword metadata were processed to construct a co-occurrence network in VOSviewer. Keywords were normalized by lowercasing, lemmatization where appropriate, consolidation of acronyms with their expanded forms, and merging of close synonyms. Non-informative terms were excluded, and a minimum occurrence threshold was applied to ensure stability of the network. Clustering used association-strength normalization and the smart local moving algorithm with a resolution parameter selected to balance granularity and interpretability. Methodological transparency is increased by reporting the chosen thresholds and by conducting robustness checks: sensitivity to resolution and minimum occurrence values, and stability assessed through document jackknifing. Where applicable, cluster quality is summarized using modularity and silhouette indices; the study refrains from overstating precision in the absence

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of full-text corpora, and encourages future work to publish detailed metrics and code to support replicability.

2.1 Research design and data collection procedure

Using a systematic literature review, this research has identified and synthesized the results of past research. Academic databases such as ScienceDirect were used for searching for literature published from 2010 through to 2025 using a comprehensive search of literature and the selection of 42 academic articles, which would form the basis of a comprehensive discussion of the topic and the development of a conceptual framework for understanding cognitive sustainability in airport operations, as detailed in Güner and Seçkin Codal, 2022; Bakır et al., 2022.

The search strategy was based on three main keywords: "sustainable airports," "people in aviation," and "airport management." Articles selected by this systematic review utilized strict inclusion criteria; selected articles only included research that demonstrated at least one aspect of the TPM framework. Additionally, strong emphasis was placed on research that illustrated the connection and relationship between all three primary components, to develop a comprehensive understanding of cognitive sustainability in airport operations

2.2 Data analysis

Thematic extraction and synthesis was carried out by using a thematic analysis. The overall findings of this literature review were organized into three themes from the group of articles selected for review. Each article was thoroughly reviewed, and the findings were categorized into three distinct categories (themes) for further analysis. The three categories and the articles that form each category are:

- Technology (T) – includes the use of artificial intelligence (AI), Robotics, and Sensor-Based Technologies (Jimenez et. al, 2023; Ku, 2024; Yildiz et. al, 2022).
- People (P) – includes specialized training, OSHA standards, and human factors (Wu et. al, 2026; Muecklich et. al, 2023; Dekker, 2004).
- Management (M) – includes strategic planning and operational decision making (Güner and Seçkin Codal, 2022; Ripoll-Zarraga and Huderek-Glapska, 2021; Güner and Cebeci, 2021; Hauptvogel, et al., 2024; Hsiao, Li, 2026; Ison, et al., 2025).

During the synthesis phase, the relationships and synergies between the three categories – Technology (T) and People (P), Management (M) – were explored by examining how technological advances affect personnel performance and managerial strategies.

2.3 Bibliometric analysis

The interconnectedness between the various research topics was confirmed visually through the use of bibliometric methods and their corresponding theoretical framework. The keyword co-occurrence (KC) analysis was performed using VOSViewer Software to assess how much strength existed in linking together certain terms that appeared in the 42 selected articles (Bakır et al., 2022). This provided researchers with the ability to build a map that demonstrated where the greatest clusters of related research areas were located within the published literature.

2.4 Coding and data integrity

In order to promote an accurate and clear approach to data synthesis, the inclusion of identified evidence within TPM interactions should occur according to the following guidelines: during the thematic extraction process, an element's dependency or causality was coded against the result's outcome. For instance, management decisions regarding the adoption of specific types of technology directly impact the training of personnel associated with that new technology (Passenier et al., 2015).

Examples from the literature were included wherever possible to assist with a solid conceptualization of the data synthesis. Specific examples collected included the use of Fuzzy Logic for measuring a candidate's subjective qualities such as personality when making a selection for hire (Skorupski et al., 2020; Fitouri-Trabelsi et al., 2013) and how airport bus operators' cooperative scheduling with their fuel suppliers impacts both the safety and

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efficiency of airport refueling operations (AlKheder et al., 2024; Cai et al., 2025).

3. Results

This section presents the key findings derived from the systematic review, structured around the TPM framework.

The analysis confirms that technology, people, and management form an integrated structure in the airport operations literature. Central terms related to airside processes, scheduling, automation, training, and governance appear as hubs that link operational performance with safety and environmental considerations. Three coherent thematic areas emerge: (i) technology-oriented studies that examine automation, sensing, and optimization; (ii) people-centered studies that analyze training, workload, and human performance; and (iii) management-focused studies that evaluate planning, coordination, and organizational culture. Rather than treating these areas as disconnected, the network reveals multiple bridges – particularly between automation and environmental efficiency, and between human factors and capacity management – suggesting that cross-domain solutions are more promising than isolated interventions.

3.1 Bibliometric evidence and core connection structure

Analysis through VOSviewer of the keyword co-occurrence network validated the proposition that technology, governance, and people operate as an integrated system. The VOSviewer map (Figure 1) demonstrates clear connections between keywords (e.g., ‘Technology’, ‘Training’, and ‘Management’) that illustrate the structural basis of the research project’s core hypothesis.

The bibliometric mapping analysis produced three major groupings of themes: (i) the Red Cluster, which relates to the concept of ‘mobility’, ‘efficiency’, and focusing on the appropriate use of available resources to lessen delays; (ii) the Green Cluster, which focuses on ‘problems’, ‘delays’, and ‘systems’; this grouping shows substantial research interest towards employing technological solutions like simulators and agent-based models for overcoming operational bottlenecks (i.e., Green Cluster); and (iii) the Orange/Yellow Cluster, which covers human factors in relation to operational processes and procedures by including topics like ‘arrival’, ‘account’, and the agent model and includes a variety of models that simulate human factors, procedures, and behaviours (Wei, Gosling, 2013; Muecklich et al., 2023; Lao et al., 2024; Teng, et al., 2026; Wang et al., 2026).

3.2 Connection 1: Technology influences people and management (T → P & M)

The performance of sophisticated technical systems depends not only on the availability of the technology but also on the qualifications of those who support and implement the system as well as how well the technology fits in with existing management practices. According to research on artificial intelligence (AI) and Computer Vision (CV) systems, one area of application of AI is in automating the identification of service activity timestamps performed on the airport terminal. This automation will enable operational personnel to filter out “potentially inaccurate turnaround information” produced by manual entry into systems (Yıldız et al., 2022) and ensure objective documentation.

In addition, AI systems need users trained to interpret the data derived from an AI-generated dataset. Hence, it is critical for management to utilize AI-generated datasets to monitor operational efficiencies of service providers that are delayed through penalties (Sivakumar, 2022; Güner, 2021).

3.3 Connection 2: Employee performance depends on management and technology (P → M & T)

Supportive managers and the proper use of technology result in both increased worker safety and performance. Ground personnel who are confronted with challenging situations (such as Unruly Passenger Behaviour – UPB) must receive training that includes more than just technical skills; they must also be given the authority by their superiors to effectively manage crises (Nounou, Shaban, 2025).

When there are not enough ground handlers, it is often due to low wages and inadequate technology. Therefore, a manager needs to look beyond just keeping costs low and think about implementing integrated strategies, such as “airport depeaking,” to alleviate employee stress (Muecklich et al., 2023; Balk et al., 2011). In addition, Fuzzy

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Logic systems are used to measure non-quantitative characteristics (e.g., personality and attention) when selecting operators for high-risk vehicles (Skorupski et al., 2020; Fitouri-Trabelsi et al., 2013).

3.4 Connection 3: Management decisions affect technology and people (M → T & P)

Strategic managerial decisions establish how to allocate resources and determine the level of operational efficiency/safety through the implementation of safety policies within their organisations. The existing "top-down" approach (Systems-Theoretic Accident Model and Processes – STAMP) for developing safety regulations had not been successful in addressing safety due to its simplistic approach. As a result, Passenier et al., (2015) suggest that management should shift their focus from establishing "top-down" policies and procedures, to integrating safety concepts into company culture (Hale and Borys, 2013).

Management's responsibility to balance competing stakeholder interests is complex. Integrated models of optimisation demonstrate that the most expedient solutions are not necessarily the least costly or least damaging to the environment. Therefore, management must make informed strategic choices about time (delay) vs. cost (fuel) for their safety programme. In addition, integrated planning efforts regarding staff rostering and task assignments result in more efficient use of staff resources and reduced staff time idle (Cappanera et al., 2024).

3.5 Coordination and environment (sustainability) findings

Environmental sustainability and efficiency are the two most important benefits of the use of the TPM framework. Model predictions from Game Theory point to the need for a more collaborative approach in the development of strategic decisions, particularly those associated with enabling the movement of cargo through smaller, strategically located transport centres (i.e. airports) using existing road and rail infrastructure thus reducing congestion at the central cargo terminal. In addition, improved predictive maintenance via AI technologies is needed in many sectors where risk is high (e.g., cold chain logistics) to help organizations manage costs and remain compliant with legal requirements.

Research into crisis mitigation, particularly (but not exclusively) in relation to air cargo diversion, indicates that merely adding additional human resources beyond the available runway capacity is not a solution to addressing problem areas during times of increased demand. Management must be able to analyse a bottleneck to determine whether that bottleneck is a result of inadequate staffing, inadequate physical runway capacity, or a combination of both.

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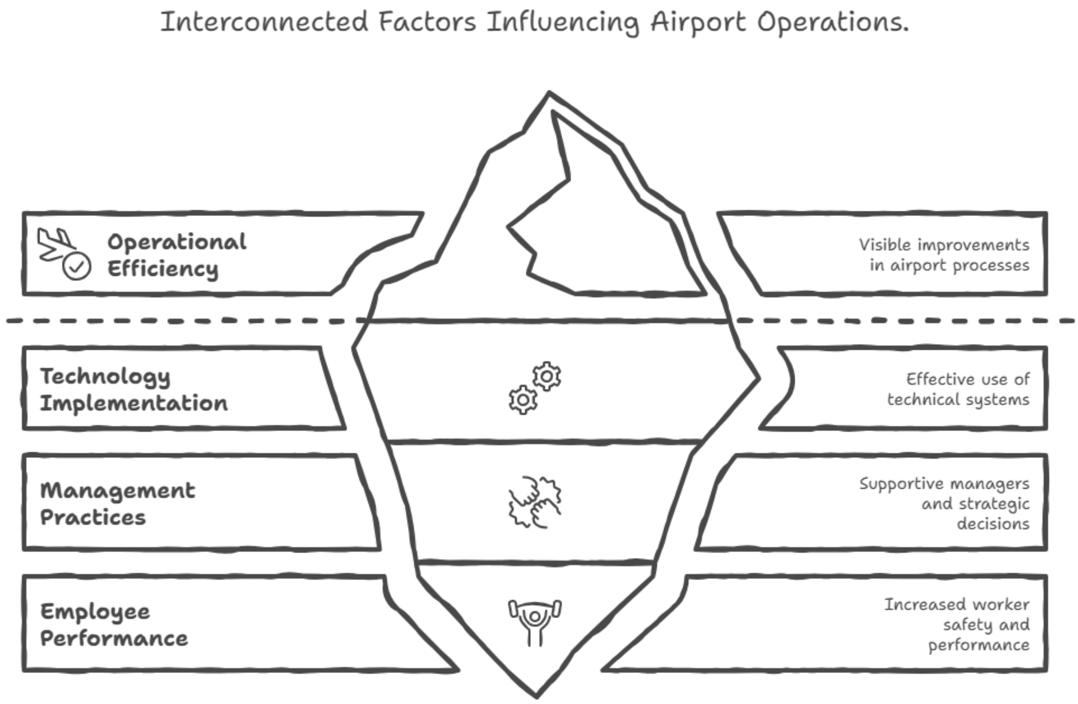

Figure 2. Connection between people, technology and management

4. Discussion

Technology influences people and management by changing information availability, task structure, and decision latencies. For example, computer vision and automated timestamp detection increase data objectivity, but their benefits are realized only when controllers and ground staff are trained to interpret outputs and when managers incorporate these metrics into performance dashboards and contractual oversight. Employee performance depends on supportive management and appropriate technology; scenario-based training, transparent escalation protocols, and modern scheduling reduce stress and error rates, whereas outdated equipment and purely top-down mandates undermine resilience. Management decisions integrate the system by setting deployment priorities, synchronizing training with tooling maturity, and balancing competing objectives such as delay reduction, fuel burn, and workload. Causality thus runs bidirectionally: adoption of new tools changes human work, which in turn feeds back into managerial strategy; conversely, strategic choices about staffing, standards, and governance shape the feasibility and impact of technological solutions.

This study's primary goal was to assess the synergistic relationship between Technology, People, and Management (TPM) within a unified framework for Airport Operations. Through a systematic review of scholarly articles, it has been clearly shown that these three areas do not work independently of each other, but rather are interdependent with each of them in a constant state of supporting and influencing each other (Bakır et al., 2022; Güner, 2021; Yıldız et al., 2022).

4.1 Technology as a driver of human and managerial effectiveness

The analysis confirms that emerging technologies, including Artificial Intelligence (AI), computer vision, and automated monitoring tools, significantly reduce human error and enhance operational accuracy. However, technology in isolation is insufficient for systemic success (Ku, 2024). Employees must be equipped with appropriate training (Oto et al., 2012; Balk et al., 2011), and managers must actively integrate data from these systems into their strategic decision-making processes (Güner and Seçkin Codal, 2022; Güner and Cebeci, 2021). Consistent with previous research, technological efficacy is contingent upon human proficiency and the updating of associated work processes (Taufik and Hanafiah, 2019; Wongyai et al., 2024; Nugroho et al., 2012). Consequently, the success of AI-driven data in airports depends on personnel understanding and managerial

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application (Jimenez et al., 2023; Ku, 2024), reinforcing the premise that technology cannot be effective without the active support of both people and management (Ansola et al., 2011; Ankersmit, Rezaei, Tavasszy, 2014; Burghouwt, Poort, Ritsema, 2014; Padrón et al., 2016,).

4.2 Employee performance as a joint output of management support and technology

The research indicates that employees perform better when provided with adequate support from their supervisors and training and instruction on how to handle stressful situations. Due to the nature of the ground staff's work, they have heavy workloads and deal with customer disputes regularly and require effective leadership support. On the other hand, low compensation and obsolete equipment create barriers to motivation and create staffing shortages. The associated literature indicates that using integrated planning systems, implementing airport de-peaking strategies and applying modern scheduling methods will help lower workplace stress so employees are more productive at work (Wu et al., 2026; Balk et al., 2011). Overall, an individual's capabilities are subordinate to the effect of technological and managerial structures on employee productivity.

4.3 Managerial decisions as the integrating force of the TPM framework

The relationship between management, technology and people is close. Management makes decisions on how best to allocate organizational resources to achieve a given organizational direction. The predominant use of top-down safety mandates has been ineffective because they have not taken into account the complexities of the work environment. A collaborative bottom-up model in which workers contribute to the development of safety rule is more effective for creating a resilient organizational culture (Passenier andet al., 2015; Hale and Borys, 2013). Managers frequently have competing interests, and decisions are often difficult due to competing priorities (Weiszer andet al., 2015). A strategic view of how to balance these competing demands is required to ensure the best use of both human and technological resources.

4.4 System-level coordination and environmental sustainability

The TPM framework goes beyond the airport level, enabling airports to positively collaborate through the implementation of shared planning and enhanced connectivity, thereby easing congestion and enhancing efficiency across the region (Zuo et al., 2025), thereby providing environmental benefits as a result of the improved performance and reduced environmental impacts associated with the implementation of predictive maintenance solutions within specific industries such as cold chain logistics (Mizrak and Cantürk, 2025). Lastly, the results shown in the studies indicate that adding more personnel alone cannot solve the bottleneck problem; however, increasing personnel is only effective when the facility meets its physical limitations of either runway or slot capacity (AlKheder et al., 2024; Malandri et al., 2020). Therefore, managers need to properly identify the root causes of operational issues in order to make informed, educated decisions.

4.5 Integrated interpretation: TPM as an interdependent system

This research indicates that airport sustainability builds on an interdependent, employee-centric framework. Employees' training must adapt as new technology is developed in order for them to make full use of data-driven insights properly (Oto et al., 2012; Ku, 2024). Employees' well-being should be the focus of management, especially in stressful operating contexts (Wu et al., 2026; Muecklich et al., 2023). The development of both operational/functional efficiency and higher levels of environmental sustainability may be accomplished by integrating the functions of personnel management with employee task planning (Cai et al., 2025; Cappanera et al., 2024). A transition to a technology-based approach to monitoring and to strategic collaboration – rather than the mere increase in the number of employees – is necessary for achieving environmental sustainability objectives (Güner, 2021; Weiszer et al., 2015).

4.6 Practical implications

Based on the findings, several practical recommendations are offered for airport managers and stakeholders. Training programs should be developed concurrently with technological implementation to ensure seamless data integration (Oto et al., 2012; Ku, 2024; Balk et al., 2011). Managers are encouraged to prioritize the psychological health and well-being of staff to mitigate burnout in demanding roles (Wu et al., 2026; Muecklich et al., 2023). Additionally, the use of unified systems for personnel and task scheduling is recommended to avoid fragmented

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and inefficient planning (Cai et al., 2025; Cappanera et al., 2024; Padrón et al., 2016). Finally, achieving environmental objectives requires a commitment to strategic collaboration and the use of technology-driven monitoring systems (Güner, 2021; Mizrak and Cantürk, 2025; Weiszer et al., 2015).

The results translate into several practical implications for the principal stakeholder groups. Regulators and policy-makers should align deployment roadmaps with measurable targets that jointly reflect safety, capacity, and environmental performance, and they should encourage data interoperability through standards and governance frameworks that reduce integration friction. Certification pathways for machine-learning decision support need explicit evidence requirements for robustness, explainability, and latency so that operational approval can proceed with confidence. Air navigation service providers should prioritize trajectory-oriented concepts that demonstrably reduce delay and fuel burn while maintaining controller workload within acceptable bounds, and they should invest in resilience through contingency planning and cross-border coordination informed by network-level analytics. Human-in-the-loop evaluations of automation during trials are essential to monitor workload, situational awareness, and mode awareness, thereby mitigating risks associated with automation bias. Technology developers and integrators should design interoperable interfaces and data models that accommodate legacy systems, embed human factors and model transparency to foster user trust, and provide uncertainty-aware optimization that incorporates weather and demand variability together with decision dashboards that make trade-offs explicit. Training organizations should update curricula to include human–AI teaming, mode awareness, and strategies for mitigating automation bias; they should employ scenario-based exercises that expose personnel to varied traffic regimes and automation levels, and they should monitor cognitive workload with validated measures to inform rostering and support tools.

4.7 Limitations and directions for future research

This study has reviewed 42 articles between 2010 and 2025 however, there are limitations regarding the representation of very small airports and newly tested technology in this study. Future research should include an example of how the newly developed technologies can be viewed within an operational environment and an analysis that can be cross-compared between countries. Further utilization of the TPM Framework will determine how interactions in air traffic control and cargo terminals will differ across various aviation environments.

The synthesis draws on a finite corpus of articles and on keyword-level metadata rather than full-text analysis, which constrains granularity and may underrepresent niche topics. Future research should expand the dataset across multiple databases, publish open corpora and code for reproducibility, and integrate full-abstract text mining with topic modeling to capture conceptual nuance. Empirical studies of human–AI teaming in operational settings, certification-constrained real-time machine learning architectures, and governance models for cross-border data sharing represent high-impact avenues for advancing both scholarship and practice.

5. Conclusion

Study results demonstrate that human performance in aviation is a product of not just how much technology can facilitate operational performance (via the provision of AI and automated monitoring systems), but also how well management can support such operations through comprehensive employee training and developing strategic management decisions, thereby achieving success in aviation business activity (Jimenez et al., 2023; Ku, 2024; Yildiz et al., 2022; Oto et al., 2012; Balk et al., 2011; Güner and Seçkin Codal, 2022; Güner and Cebeci, 2021). Thus, TPM represents an appropriate model for the development of cognitive sustainability, as evidenced by the fact that it incorporates all three elements of Technology, People, and Management into a single framework that allows for enhanced coordination between all stakeholders in the aviation industry. A coordinated approach to developing cognitive sustainability through the implementation of the TPM framework provides benefits to both individual airports and the aviation system as a whole. Moreover, a transition from traditional "top-down" management structures toward a more inclusive "bottom-up" safety culture, in which employees have the opportunity to participate in the creation of aviation regulations, is necessary to reduce the stress and pressure associated with ground handling operations in airport environments. Finally, the use of TPM will enable airports to achieve greater environmental and operational sustainability in the long term (Zuo et al., 2025; Weiszer et al., 2015).

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The human ecological significance of urban green spaces

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Abstract

The proportion of the world's population living in cities is steadily increasing, intensifying pressure on natural resources and urban ecosystems, particularly in historically developed large cities. Urbanisation poses significant environmental challenges, including biodiversity loss, habitat fragmentation, and deteriorating urban climate conditions. This study aims to highlight the role of sustainable urbanisation and urban green infrastructure in mitigating the negative environmental and social impacts of urban growth, with a particular focus on biodiversity conservation, ecosystem services, and human well-being. The paper is based on a comprehensive review and synthesis of international and Hungarian scientific literature, policy documents, and urban planning concepts related to sustainability, green spaces, biodiversity, and urban ecology. Comparative examples from European cities are used to illustrate best practices in integrating green areas and ecological networks into urban structures. The analysis demonstrates that urban green spaces – regardless of whether they are of natural or artificial origin – provide essential ecological, climatic, social, and health-related functions. Well-connected green networks reduce habitat fragmentation, mitigate urban heat island effects, improve air quality, and contribute to physical and mental health. Furthermore, large, integrated green areas can significantly enhance urban sustainability and resilience. Preserving and expanding urban green spaces and ecological networks is a key prerequisite for livable, climate-adaptive, and healthy cities in the context of ongoing urbanisation.

Keywords

urbanization, green spaces, urban development, biodiversity, sustainability

1. Introduction

An increasing proportion of the world's population lives in cities. In 2024, 58% of the world's population lived in urban areas, while in Europe this proportion was even higher: in 2023, 76% of Europe's population resided in urban areas (World Bank, n.d.). Contemporary urbanization threatens both natural values and resources, and effects are the most significant in large cities established a long time ago (Goudie and Viles, 1997).

In order for the continuously growing urban population to exist in a livable environment, it is necessary to prioritize sustainable urban development as a settlement development goal. The primary objective of sustainable urban development is to create an environmental, economic, and social balance in cities through the efficient use of natural resources. The common goal of sustainability measures is to ensure economic and social development through the application of environmentally friendly technologies and the improvement of environmental conditions.

Therefore, concept of sustainability can be divided into economic, social, and environmental sustainability components. The first concerns the equitable distribution of resources, the second relates to public and civic participation, while the third focuses on the protection of natural resources. Sustainability can only be achieved through the parallel and simultaneous implementation of these three dimensions (Akkoy et al., 2025) (Figure 1).

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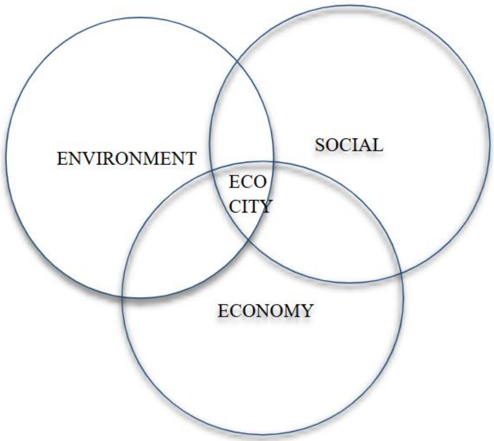

Figure 1. Dimensions of sustainable development
(based on Akıncı, İ. and Pouya, S., 2019: 97)

Sustainability in a settlement can only be achieved through appropriate planning based on ecological principles. To this end – among other things – biodiversity must be protected by preserving the green areas surrounding the city and by protecting and restoring local ecosystems and wetlands (Miller and Spoolman, 2008). Furthermore, it is important to be aware of the concept of sustainable urban development and its human ecological foundations. Green developments, as outlined in the environmental programs or urban development concepts of Hungarian cities, are gradually being implemented. However, there is still much to be done in this area. Our cities are characterized by increasing traffic, shrinking green spaces, and asphalt-covered roads, which need to be counterbalanced by sustainable development initiatives. There are many European best practices for these, which Hungary can also adopt. Furthermore, it is crucial to draw attention to the fact that the significance of urban green spaces is not only an abstract concept of environmental protection and nature conservation, but it also has practical importance for ensuring human well-being and a healthy environment.

This study explores the relevant literature to show the importance of green surfaces and areas in cities, and thus in sustainable urban development. The aim is to present the reasons for creating so-called green cities, and to show their significance from a human ecology perspective. For illustration, some practical examples of sustainable urban development from major European cities are also presented. The rest of the paper is organized as follows. Section 2 clarifies the fundamental concepts related to sustainable urban development. Section 3 offers an overview of the different functions of green areas, while Section 4 describes best practices from Europe. Section 5 concludes the article.

2. Background

This section discusses the most important concepts related to sustainable urban development. These include green surfaces and green areas, biodiversity and green cities.

It is important to clarify the difference between *green surfaces* and *green areas*, as these terms are often used interchangeably. The totality of vegetation-covered areas within settlements is referred to as *green surface* (Molnár Zs., 2020). The surface of settlements can be divided into biologically active (green surfaces + water surfaces) and biologically inactive (built-up, paved) parts. In contrast to green surfaces – which represent a functional space – *green areas* constitute a land-use category to which specific legal regulations apply. Green areas form part of the green surface system and include only public spaces. It is important that they are accessible without barriers from public roads and squares. Furthermore, they may only be used for sports and recreational purposes. Green areas include public parks, public gardens, tree-lined public spaces, playgrounds, and dog parks. It is worth noting that private gardens are no longer considered green areas, only green surfaces, since they do not function as community spaces (Levegő Munkacsoport, n. d.).

It is also important to interpret the concept of biodiversity, as it is widely used from political decision-making to scientific discourse. However, this concept is still not sufficiently well known to the general public, and thus it is generally attributed aesthetic or emotional value rather than functional or economic value. Biodiversity is the variety of living things – animals,

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plants, fungi and microorganisms – that live in one area (Hancock, n. d.). Urbanized green areas increasingly serve as sites for the preservation of native biodiversity. As the spatial extent of urban areas continues to grow, natural habitats within settlements are becoming increasingly fragmented. Urban infrastructure – roads, real estate developments, and other linear infrastructure – disrupts the areas of natural flora and fauna. This disruption gradually degrades local biodiversity (Kisvarga, 2023). Additionally, the genetic stock of organisms living within these fragments also deteriorates.

The increase of green spaces and the protection of biodiversity cannot be understood without the concept of the green city. A green city, or in other words, a sustainable city or even eco-city, is an urban enclave where construction, planning, and operation prioritize the preservation of the natural environment while also ensuring the social, economic, and health well-being of its residents (Loughlin, 2024). The administrative framework for making cities more sustainable is defined within the European Union by the Green City Accord (GCA). This is a movement aimed at European cities that supports the creation of greener, cleaner, and healthier urban environments (EC, 2020).

3. Functions of green surfaces and areas

It is important to emphasize that from a settlement ecology perspective, it is almost irrelevant whether urban green surfaces are of natural or artificial origin, as the plants forming green surfaces provide various ecosystem services. They greatly contribute to improving environmental quality, mitigating the negative impacts of human activities, and enhancing aesthetic value (Kisvarga, 2023).

Due to the changed and gradually warming climate, these negative effects on wildlife are intensifying. This particularly affects the wildlife in built-up areas as well as the humans living there. Several studies have shown that in cities or neighborhoods with a lot of green space, people are happier and there are fewer individuals with mental health issues (Liu et al., 2023; Zhang et al., 2024). The likelihood of modern age diseases such as migraines, depression, and panic disorder developing is also lower than elsewhere. One reason for this may be that people are fundamentally connected to the natural environment, so a plant-covered environment has a calming effect, and stress factors do not manifest as strongly. The economic significance of this can be seen in the fact that the mental well-being of people (employees) leads to more efficient work. This, in turn, can positively influence GDP in the long run (Kisvarga and Orlóci, 2025). In addition, financial benefits also include the reduced healthcare costs that can result from the absence of mental illnesses. Therefore, the presence of green spaces is of paramount importance to human quality of life.

Urban green surfaces do not only provide direct ecological benefits but also fulfill numerous functions related to human factors. According to Statuto et al. (2021), these may include the following functions:

- ecological-environmental function;
- protective function;
- aesthetic-architectural function;
- social and recreational function;
- cultural and educational function;
- health and hygienic function.

Areas covered with plants may have the following primarily ecological functions according to Finke (1996):

- climate protection;
- protection against solar radiation;
- air purification;
- soil protection;
- protection of scientific and cultural values;
- protection of biotopes and ecosystems;
- landscape protection;
- provision of leisure and recreation.

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According to the above, urban green surfaces/areas possess numerous human-related functions. These include, according to Gábor and Jombach (2008):

- social functions (physical and mental recreation, nature-oriented agora);
- economic functions (increase in property values, enhancement of economic attractiveness);
- aesthetic functions.

Above all, however, the ecological (natural habitats, green corridors) and environmental protection functions of green surfaces and areas, such as noise and vibration reduction, dust filtration, water retention, are the most widely recognized human-related functions. Meanwhile, out of environmental functions, which influence environmental quality in urban environments, the air-conditioning and microclimatic effects of green surfaces/areas are the most important ones (Gábor and Jombach, 2008).

From the perspective of urban life, the greatest short-term health risk is caused by excessive warming. This is exacerbated by the increasing appearance of unplanted, paved heat islands over larger areas. This is the so-called urban heat island effect, which essentially means what we experience day by day in less vegetated urban environments. The decreasing vegetation cannot counteract the summer heat, while the human-made environment is unable to absorb the thermal energy of solar radiation; rather, it amplifies it. Thus, it can increase the temperature of paved public spaces by as much as 30–40 °C – creating a kind of heat island (Kisvarga and Orlóci, 2025). The costs of climate change will also largely be borne by cities – especially densely populated metropolises: increased temperatures and extreme weather events in cities will have alarming consequences for the urban population. Increased mortality may also be expected. For example, the increasingly frequent European heatwaves cause tens of thousands of deaths. The health of marginalized or elderly people, in particular, will be primarily affected by urban heatwaves and urban heat islands (Mocca et al., 2020).

In addition to evapotranspiration, trees cool the surrounding environment by shading the surface. Tree branches and leaves prevent incoming solar radiation from reaching the ground surfaces below the canopy. Typically, trees effectively block 70-90% of solar radiation in the summer and 20-90% in the winter. The location of the tree affects its effectiveness in cooling buildings, as trees on the west or southwest side of the building block most of the solar radiation from the building (Texas Trees Foundation, 2017).

A significant relationship has been found between human health status and the extent of green areas near places of residence. This relationship can be explained by the fact that the greater the proportion of usable green areas, the more people use them. Green areas have beneficial effects on alleviating mental fatigue, promoting physical activity, and may also reduce mortality rates. Furthermore, green areas have a stress-reducing effect (Schipperijn et al., 2010).

The relationship between human health status and green surfaces can be traced in (Western) European policy measures. In several national and local policy areas, such as urban development plans, the positive effects of green area use are mentioned. Some of these policy measures have made it clear that increasing green areas and improving their condition are of outstanding importance for human healthcare (Schipperijn, 2010). This is supported by Perényi (1975), who mentions both the health-protective and social functions of green areas (Table 1). Health-protective roles include, for example, the balancing of climatic conditions, filtration of dust and other air pollutants, noise reduction and dampening effects, and hindering the spread of fire. Social functions include making daily work, leisure, and living conditions more balanced and pleasant in an appropriate green environment.

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Table 1. Importance of urban green spaces (own editing, based on Perényi, 1975)

Healthcare	Recreation	Settlement climate	Environmental protection	Nature conservation
treatment of respiratory diseases (e.g. cave therapy)	hiking	protection against wind	CO_2 sequestration	preservation of biodiversity
psychological effects	excursions / trips	protection against solar radiation	noise barrier function	preservation of geodiversity
–	active/passive recreation	evapotranspiration of vegetation	hydrological protective function, water retention	ensuring ecological corridors
–	wildlife and plant observation	reduction of temperature anomalies	landscape protection	

The role of urban green areas in urban climate, including protected areas, is also emphasized by Radó (1985). According to him, the foliage mass of trees acts as a filter, enabling them to capture about 70% of the generated dust. One hectare of dense tree planting can capture approximately 30–60 tons of dust during the vegetation period.

Owing to the versatile benefits of green areas, by 2025, an increasing number of "green developments" aimed at sustainability have been launched in European cities, especially in EU capitals, with the clear goal of improving the quality of life for residents and making the settlements more livable. The next section shows a selection of these developments.

4. Best practices

To counterbalance the negative effects of urbanization, and in order to protect biodiversity and preserve green surfaces, several European cities maintain green belts and integrate extensive natural areas into their spatial structure. European cities with large green areas include Vienna, Ljubljana or Copenhagen, extensive green areas are almost embedded in the city center (Figure 2.). Furthermore, the city of Helsinki has developed an extensively used, integrated green surface network. Meanwhile in Stockholm, there are approximately 100 parks and 7 large protected areas, which together cover about 40% of the city area (Mason, 2003).

Table 2. Top 10 Greenest Cities in Europe in 2025 (Essential Living, 2025)

Rank	City, Country	Description
1	Oslo, Norway	Exceptional green space, high life expectancy, top air quality
2	Stockholm, Sweden	Strong sustainability measures and public transport
3	Vienna, Austria	Excellent urban green coverage and quality of life
4	Ljubljana, Slovenia	Increasing green infrastructure and livability
5	Copenhagen, Denmark	Progressive eco-initiatives and bike-friendliness
6	Lisbon, Portugal	Balanced green index and relaxed lifestyle
7	Tallinn, Estonia	Clean air, growing green spaces
8	Vilnius, Lithuania	Strong environmental strategy and green space access
9	Amsterdam, Netherlands	Vast canals, parks, and cycling infrastructure
10	Paris, France	High-quality urban green amenities despite dense population

The preservation of green, vegetation-covered areas – regardless of their classification – is a fundamental principle of sustainable urban living. Therefore, protecting and increasing urban green surfaces represents a serious task for both city leadership and local communities (Lányi, 2000). Nature conservation also supports this task, as it can counteract the negative processes and phenomena of urbanization (Goudie and Viles, 1997).

Today, an important development trend can be observed in (Western) European cities, whereby ecological networks are being created or existing ones are being developed in urbanized areas. This is particularly evident in Dutch cities, where central and local governments jointly make efforts to develop and protect existing and future ecological networks (Mason, 2003). A similar development direction was articulated by Perényi (1975), according to whom the green surface system has a prominent role in shaping urban structure, as vegetation-covered areas have multifunctional roles depending on their size and quality. Furthermore, when designing urban green surface systems, efforts should be made to ensure that green areas form a coherent whole and are not fragmented or isolated from one another. Therefore, urban green surfaces should not only

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be connected to each other but also to the large green areas surrounding the city, thereby ensuring, among other things, urban air circulation.

These urban-level ecological networks include some linear structures, such as watercourses and rows of trees which provide connections between parks and other public spaces and community areas. The ultimate goal of developing these ecological networks is to create a common, Europe-wide network.

Green cities strive to ensure that their urban development plans are aligned with urban climatological requirements. In some German cities, such as Freiburg or Stuttgart, building restrictions have been introduced in urban ventilation zones. Recognizing the importance of green areas in urban climate, the forests within the administrative area of Oslo, for example, are treated as protected areas (Mason, 2003).

In 2025, there are many international practical examples of how to make it a city green. Some of these developments could be transferred to Hungary as well.

- Copenhagen, Denmark: A leader in cycling infrastructure with extensive super cycle highways (The Climate Reality Project, n. d.).
- Stockholm, Sweden: The first European Green Capital (2010), known for sustainable planning, efficient public transport (The Climate Reality Project, n. d.).
- Ljubljana, Slovenia: Features extensive car-free zones in its center, abundant green space and its pedestrian-friendly city centre (Glasco, 2022).
- Milan, Italy: Known for "Bosco Verticale" (Vertical Forest) skyscrapers, integrating nature into buildings to boost biodiversity and reduce pollution. The project consists of two residential towers of 110 and 76 meters in height, located in the center of Milan, in the Porta Nuova district, hosting 800 trees, 4,500 shrubs, and 20,000 plants from a hundred different plant species (Stefano Boeri Architetti, n. d.).
- Vienna, Austria: Ecologically sensitive and health-oriented urban development and green spaces (Mocca et al., 2020).
- Vilnius, Lithuania (2025 Green Capital): Planting of over 68,000 trees and shrubs. Due to the intensive expansion of urban green spaces, over 94% of local residents now live within 300 meters of a park or natural area (Eurocities, 2025).
- Villach, Austria: Planting forest by Miyawaki method (Nastran et al., 2025) (Figure 2).
- Budapest, Hungary: Development of large parks, forests, and nature conservation (Budapest Főváros Főpolgármesteri Hivatal, n. d.).

In addition to planting tree rows, a new initiative, the planting of so-called micro-forests, is also underway. A micro-forest is an area of dense plantings, typically between 100 m^2 and 3000 m^2, which mimics a natural forest. It includes many native plant species and fits well into the urban environment. For example, since 2016, the Urban Forests association has planted more than 130 micro-forests in Belgium and France using the Miyawaki method (Urban Forests, n. d.). The Miyawaki Forest (MF), also known as a mini-forest or pocket forest, originated from a rapid reforestation method developed by Japanese botanist Akira Miyawaki in the 1970s, which has gained worldwide attention. This method represents a paradigm shift in ecological restoration, as the Miyawaki method offers a fast and effective approach to creating native forests in degraded or urban environments (Webber, n. d.). The MF concept emphasizes native species, dense planting, and soil preparation, promoting rapid forest development and increased biodiversity (Nastran et al., 2025).

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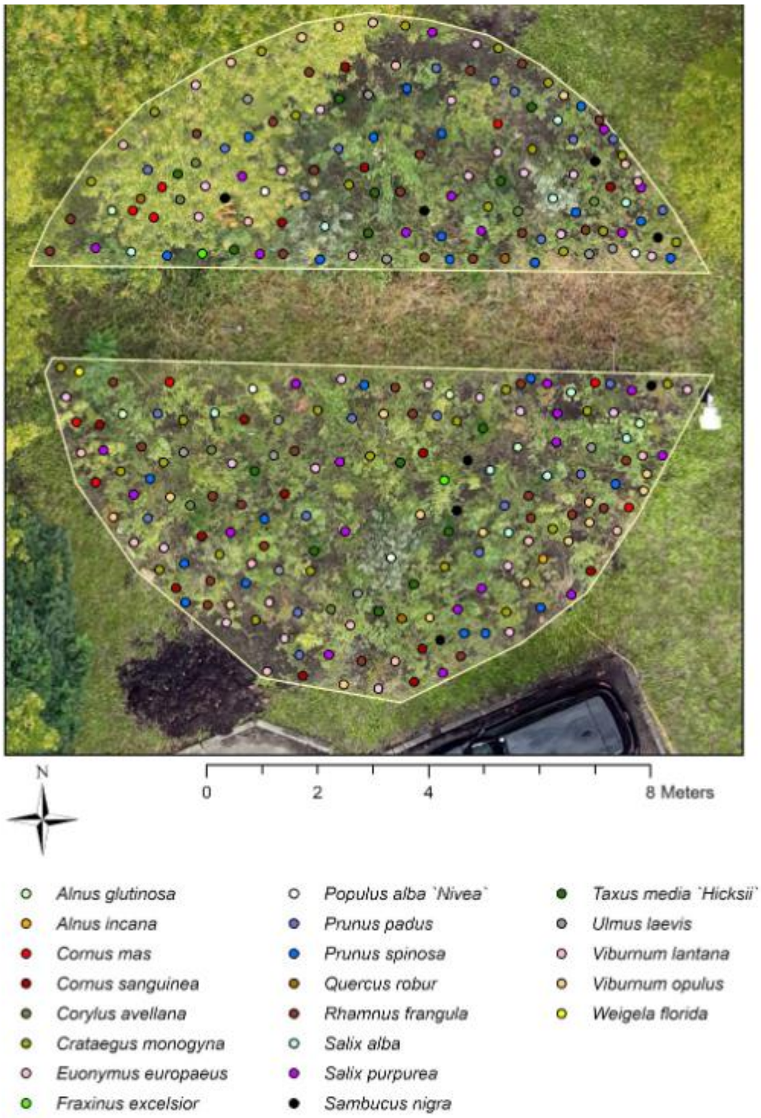

Figure 2. Visualization of the Miyawaki Forest planting from above in the Carinthia University of Applied Sciences in Villach *(Nastran et al., 2025, Figure 4)*

5. Conclusion

Urban green spaces play an important role in urban development, so their role needs to be re-evaluated during the urban planning process. This requires the will of local decision-makers, so local governments must take a leading role in these processes. Unfortunately, nowadays sustainability developments are often pushed into the background because social, infrastructural, and economic measures have priority. Additionally, economic actors are mainly interested in the development of urban infrastructure and other investments. This not only hinders the implementation of green concepts but also the exploration of potential research directions, as these are contrary to economic interests.

Despite all this, significant sustainability-oriented developments have been realized in several major European cities, including Budapest, in recent years. The expansion of green areas, the development of existing ones, and afforestation have improved the quality of life for urban residents. These developments are also necessary due to the increasingly intense warming, because the negative effects of climate change are more pronounced in the urban environment, for example, due to the heat island effect.

All in all, urban green spaces significantly contribute to the quality of life, well-being, and health of the population in everyday life. Therefore, green space developments should be considered a long-term investment, not a short-term cost.

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Development Tendencies in Air Traffic Management

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Abstract
This paper investigates the evolution of research themes in Air Traffic Management (ATM) between 2014 and 2024 using keyword co-occurrence analysis. Five dominant clusters—safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability—are identified and interpreted through a socio-technical lens. Beyond describing clusters, the study examines inter-cluster dynamics and situates findings within the policy frameworks of the ICAO Global Air Navigation Plan (GANP) and the European SESAR ATM Master Plan. The use of explicit criteria for keyword normalisation, clustering parameters, and validation metrics enhances methodological transparency. The paper proposes a targeted research agenda for underexplored areas, such as the practical integration of UAS and real-time machine learning in ATC operations. Finally, it outlines practical implications for regulators, ANSPs, technology developers, and training programs, and recommends methodological innovations.

Keywords:
Air Traffic Management; VOSviewer; Bibliometric Analysis; Safety; Capacity Management; Sustainability; Trajectory-Based Operations; Automation.

1. Introduction

Air Traffic Management (ATM) is the cornerstone of the current airspace system. It handles the efficient flow of aircraft through congested airspace (Dmochowski, 2017; Madhwal, 2017, Chen, et al., 2025). However, the continuing increase in global traffic flow means that the requirement for effective ATM solutions has also been on the rise (Gu & Wan, 2020; Esteve & Zanin, 2025). This is in addition to the inherent challenges in the field of ATM. These areas include sector saturation, workload, weather-related disruptions, capacity constraints, and the impact on emissions (Skorupski, 2017; Socha, 2020; Hamdan, 2022). Thus, the field of ATM is beyond the purely technological. While many research works focus on specific aspects of the ATM system, such as conflict resolution, delay propagation mechanisms, or the safety aspect of the system, the research landscape in the ATM system does not provide an integrated overview of the broader framework of research work carried out over the past ten years 4. To achieve the aforementioned research objectives, the proposed research focused on the bibliometric analysis of 50 carefully selected research articles on ATM from 2014 to 2024 through VOSviewer. The research questions of this paper are:

- What are the prominent themes and clusters in ATM research?
- How do the themes link to technology, operations, and the environment?
- Which fields of research are being developed further, and in what areas lies the untapped potential

The map (Fig. 1) displays the main keywords appearing in ATM research and their relations.

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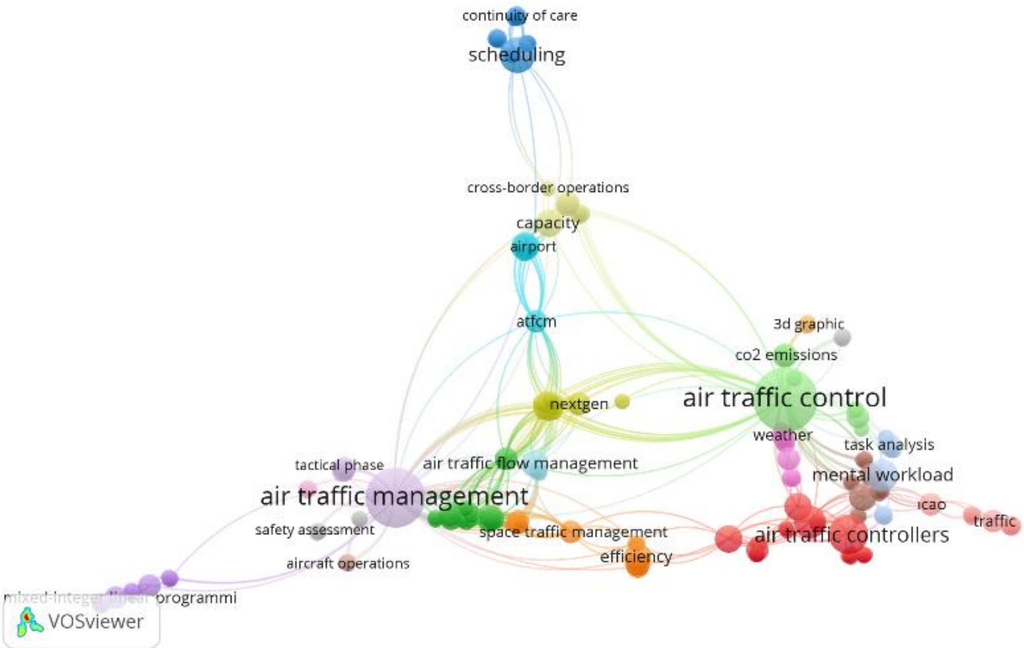

Figure 1. Keyword Network Map Generated with VOSviewer
(source: own compilation)

Larger bubbles visualise more frequent keywords, while colours correspond to the main research clusters: safety, capacity, automation, trajectory-based operations, and sustainability. Based on this, the following hypotheses were formulated:

H_1: The research on Air Traffic Management (ATM) from 2014 until 2024 is organised around five prominent research themes, including the areas of safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability and environmental impacts, which are determined by means of bibliometric cluster analysis.

H_2: Automation, machine learning, and UAS integration are the keywords, and there is a marked corresponding increased importance in the research on ATM in the latter years of the 2014-2024 decade.

This study primarily focused on grasping the major research topics of ATM within a ten-year timeframe (2014-2024) and explaining the relationships among these research topics. Hence, a bibliometric approach was used by analysing 50 peer-reviewed articles in ATM using VOSviewer. The steps involved in keyword cleaning, cluster creation, and keyword network visualisation are explained. The structure of the paper is as follows: the literature review, including research trends, cluster explanations, and gaps, is presented in Section 2. Section 3 describes the methodology. Section 4 then displays the analysis results. Section 5 discusses the findings, while Section 6 describes the practical implications. Section 7 concludes the study.

2. Literature Review

2.1. General Trends in Air Traffic Management Research in the Last Ten Years

We interpret the ATM research landscape as a socio-technical system wherein human actors, technologies, procedures, and regulations co-evolve. Drawing on innovation diffusion perspectives, automation and digitalisation are framed as enabling innovations whose adoption depends on perceived performance gains, compatibility with existing operations, and regulatory support (Torres, 2012; Standfuss, 2024). At the policy level, the ICAO Global Air Navigation Plan (GANP) and the European SESAR ATM Master Plan define capability sets and deployment priorities that directly motivate research in safety enhancement, capacity optimisation, performance-based operations, and environmental sustainability. Overall, ATM research has been growing

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steadily between 2014 and 2024 (Bowman, 2025; Balta, 2024; Brangier, 1990). Increased traffic volume, capacity constraints, safety requirements, and environmental concerns primarily drive this growth. During the early years, from 2014 to 2017, most research focused on safety issues, collision risk models, controller workload, and traditional air traffic control operations. After 2018, the research topics began to shift. Research began to focus more on digitalisation, automation, data-driven decision-making, machine learning, sustainability, and the enhancement of flight trajectories (Jimenez, M. A., Tello, F., & Mateos, A. 2020; Standfuss, 2024; Torres, 2012). In recent years, the integration of unmanned aircraft systems -also referred to as drones- modern ATC technologies, and new communication and navigation systems has also become a leading topic.

In total, over the past ten years, a trend from classic ATC procedures towards more modern, technology-supported, and environmentally aware ATM practices has become obvious:

- Lowercasing and lemmatisation of keywords (e.g., 'models'→'model').
- Acronym consolidation (e.g., 'ATC' merged with 'air traffic control').
- Synonym merging (e.g., 'UAS' and 'drones').
- Removal of stopwords and non-informative terms (e.g., 'study', 'approach').
- Minimum occurrence threshold: ≥3 across the corpus.
- Co-occurrence window: article-level (keywords appearing within the same article).

2.2. Cluster Analysis

The keyword-based cluster analysis aimed at identifying the thematic structure of ATM research published over the period 2014-2024. The analysis utilised the VOSviewer software to conduct a keyword co-occurrence analysis, determining the frequency with which a given term appears in conjunction with other terms throughout the selected articles. Keywords were automatically grouped into clusters based on the strength of these co-occurrence relationships, which represent different thematic dimensions of research within the ATM literature. This type of clustering enables the systematic exploration of the relationships that exist among the various topics covered by research, providing an overview of how the ATM research area has evolved. Overall, the performed analysis identified five major research clusters that are representative of the dominant thematic areas shaping ATM studies during the analysed period. To enhance rigour and reproducibility, the keyword handling and clustering parameters are specified below, along with the corresponding validation procedures (Dmochowski, 2017).

2.2.1. Cluster 1: Safety and Risk Management

This cluster encompasses studies assessing safety, collision risk analysis, human error, and workload of sectors within Air Traffic Management systems. Safety has always been a key domain in research on ATM, particularly due to increased traffic density and a rise in operational complexity. Various previous studies have extensively examined methods for reducing collision risk, improving situational awareness, and enhancing the performance of air traffic controllers under high-workload conditions (Skorupski, 2017; Socha, 2020; Suárez, 2024; Dönmez, Çetek, Kaya, 2022; Stamenić et al., 2025; Vrancken, Cabon, Frantz, 2025).

The strong concentration of safety-related keywords within this cluster confirms that safety and human factors remain a primary pillar of ATM regulations. That is, operational safety and controller workload management remain central challenges in air traffic systems (Philippe, 2025).

2.2.2. Cluster 2: Capacity and Airspace Efficiency

The following cluster covers research related to capacity improvement, airspace design, sector configuration, and delay management in Air Traffic Management systems. The studies within this cluster address the challenges of increasing traffic demand through more efficient airspace structuring and capacity optimisation, while maintaining the required level of safety (Reva, Borsuk, 2015; Shamsiev, 2022). Earlier, several studies have focused on the strategies for airspace sectoring, managing traffic flow, and finding optimisation-based approaches to balance demand and capacity in strongly congested airspace environments. (Edwards, et al., 2016; Dmochowski, 2017; Madhwal, 2017; Hilton et al., 2019; Edwards et al., 2023; Standfuss, 2024, Dhief, et al., 2025; Reynolds 2014; Weigang, 2021; Zombré et al., 2025).

This cluster being most prominent makes clear that capacity and airspace efficiency are the critical operational bottlenecks in research within ATM. The results reveal that optimising airspace structure and traffic flow has

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been the primary key interest for sustaining system performance under increasing traffic volume (Jou, Kuo, Tang, 2013; Pacaux-Lemoine, Debernard, 2000; Pang et al., 2023; Pavlović, Jovanović, Stanojević, 2023; Pavlović, Stanojević, Jovanović, 2025).

2.2.3. Cluster 3: Automation and Digitalisation

This cluster encompasses studies on automation aid tools, machine learning methodologies, and decision support systems designed to enable data-driven operations within the domain of Air Traffic Management. The studies included in this cluster focus on the growing importance of algorithms and computational approaches in supporting air traffic controllers in making more informed decisions. Recent studies on this topic have demonstrated the use of machine learning and optimisation algorithms in handling complex air traffic scenarios and facilitating real-time decision-making in air traffic management systems (Jasek, 1995; Jimenez, Tello, Mateos, 2020; Standfuss, 2024; Torres, 2012; Tafur et al., 2024).

The density of automation- and digital transformation-related keywords in this cluster suggests a notable trend in the direction of ATM research. This establishes that the theme of automation is fast becoming a force that will shape the future of ATM systems.

2.2.4. Cluster 4: Trajectory-Based Operations

This research focuses on management-related studies in flight trajectory planning, conflict resolution, and the optimisation of Air Traffic Management. This research conducts studies on how to increase traffic performance in the airspace environment by improving the predictability of flight trajectories, minimising delays, reducing fuel consumption, and improving traffic flow. Recent studies have explored trajectory planning algorithms, conflict resolution algorithms, and optimisation algorithms to enhance airspace efficiency and reduce its environmental impact (Dmochowski, 2017; Madhwal, 2017; Oehme, 2010; Guo, Bard, 2024; Rosenow, Fricke, 2019).

The presence of trajectory-based operations in this group highlights a significant research focus on performance and predictive approaches for air traffic management. These results indicate a key link between trajectory-based optimisation and integrating established air traffic control procedures with optimised approaches (Louie, Tai, Liem, 2025; Luu, et al., 2021; Sheeja Rani, Aburukba, 2025).

2.2.5. Cluster 5: Sustainability and Environmental Impact

This cluster includes fuel consumption, emissions, noise reduction, and green ATM strategies. In fact, most current ATM studies focus on how air traffic operations can be made more sustainable due to growing environmental concerns worldwide (Pongsakornsathien, et al., 2025; Salmon, 2025).

The cluster analysis indicates the emerging role of sustainability and environmental factors in the context of air traffic management studies. The evidence suggests an increased interest in sustainable ATMs from an environmental sustainability perspective, with sustainability now strongly associated with optimisation and the long-term efficiency of the system (Rezo et al., 2023).

2.3. Keyword Network

The keyword network developed with VOSviewer visualises the connectivity of the main topics of ATM research. Each bubble in the bubble map represents a keyword, and the frequency of occurrence of the keyword in the articles determines the size of the bubble. Keywords that are closely related have stronger connections.

In the map, five major colour groups related to factors such as safety, capacity, automation, trajectory-based operations, and sustainability can be identified. Central keywords, including "air traffic control," "safety," and "capacity," form the largest bubbles, indicating that these words are of great importance in the field. Newer topics, such as "machine learning" and "UAS," also appear, indicating a growing focus on technology and innovation.

2.4. Research Gaps

Although ATM research has grown significantly within the last decade, several gaps remain. Most studies have focused on the areas of safety and capacity, whereas fewer works have been conducted on how automation and

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machine learning can be applied in practical, real-world operations. Similarly, few studies have touched on the integration of UAS in controlled airspace. Only a few studies focus on environmental impacts and/or sustainable ATM strategies. These gaps indicate that there is still a need for more modern, technology-based, and environmentally focused research in the field of Air Traffic Management.

3. Methodology

Table 1. Summary of the Methodology

Step	Description
Data Source	50 ATM articles collected from ScienceDirect and Web of Science
Analysis Tool	VOSviewer is used for keyword co-occurrence and network visualisation.
Procedure	Data extracted → keywords cleaned → VOSviewer → 5 clusters identified.

(source: own compilation)

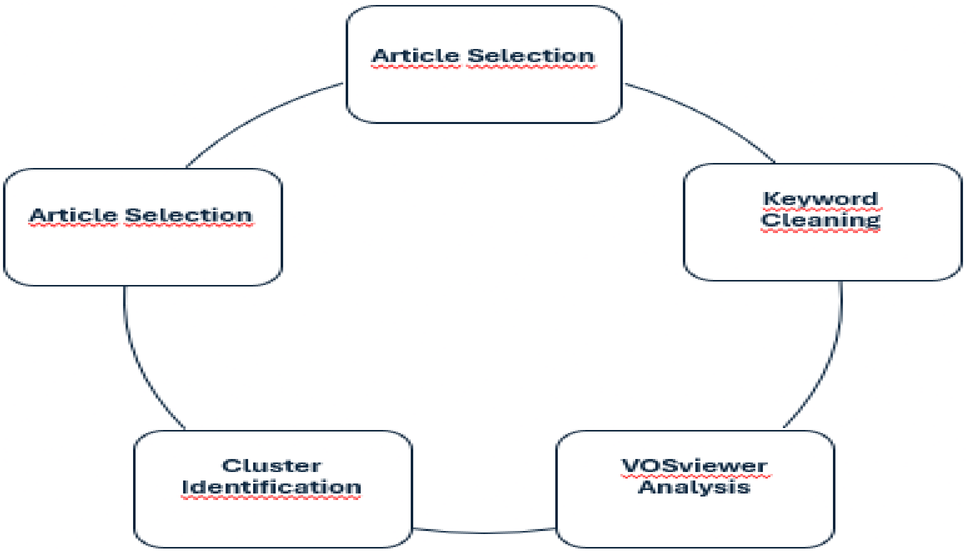

Figure 2. Methodological flowchart of the bibliometric analysis process
(source: own compilation)

4. Results

The keyword co-occurrence analysis of the 50 ATM-related articles produced a dense network of interconnected research themes. As can be seen from the VOSviewer map, this is a highly clustered structure, where particular concepts tend to group naturally into clusters due to their frequency and co-occurrence in the literature. Five big research clusters were identified that corresponded to the dominant subject areas in the 2014–2024 ATM landscape. With respect to the original analysis, the augmented corpus reveals a more intricate and interconnected keyword relationship structure, as well as a clear strengthening of relationships in the areas of air traffic control, air traffic flow management, and human factors.

4.1. Overall Network Structure

Figure 3 represents a highly clustered map, where core terms such as air traffic control, air traffic flow management, airspace sectoring, algorithm, capacity, and safety are located at the centre of the network. These keywords serve as hubs in connecting operational, technological, and environmental research directions.

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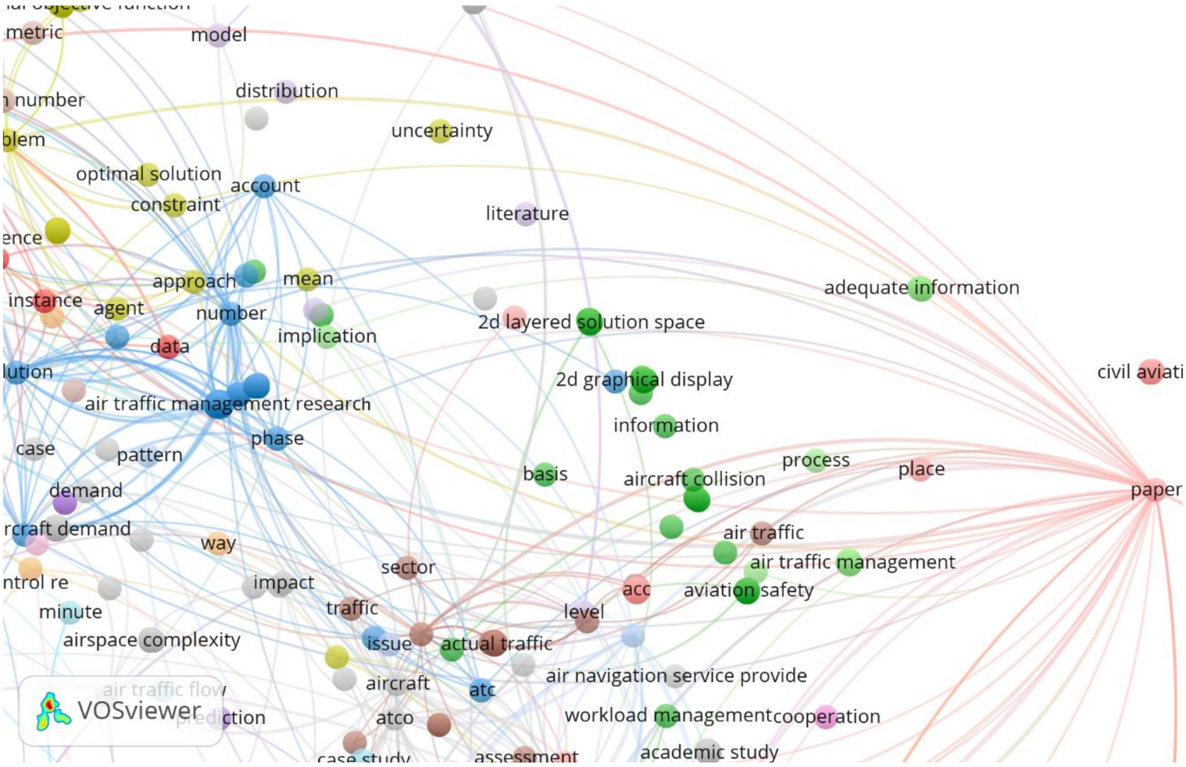

Figure 3. *Keyword co-occurrence network in Air Traffic Management literature, illustrating the relationships and interactions between core research themes and highlighting the interconnected structure of operational, safety, and management-related concepts. (source: own compilation)*

In the keyword co-occurrence network map, each bubble represents a keyword identified in the analysed ATM articles, and the size of each bubble shows how often this keyword appears in the current body of literature. Accordingly, larger bubbles represent keywords with higher usage in ATM research. The position of each bubble also indicates how closely they relate to each other, as keywords that appear together in ATM research are positioned closer together. The links in this visualisation represent the relationship of keyword co-occurrence.

Different colours in the network map denote different research groups identified by VOSviewer. Although each cluster is designated to a particular field of study, it is crucial to realise that links exist between clusters, showing the interdisciplinary nature of ATM research. It should be noted that, for example, strong connections between safety-related and capacity-related clusters demonstrate the close relationship between operational safety and efficient airspace utilisation within modern Air Traffic Management systems.

Network density shows that research in ATM is concentrated around four key areas of interest:

- air traffic flow / ATFM
- sector configuration and capacity
- Algorithmic methods and optimisation.
- safety-related keywords included collision risk, information accuracy, and cognitive load.

These dense regions reflect the most active areas of ATM research between 2014 and 2024.

4.2. Identification of the Five Clusters

4.2.1. Cluster 1 – Safety and Human Factors

The findings of Cluster 1 bear a direct relation to the literature review in Section 2.2.1 and the significance of safety and human factors in Air Traffic Management studies. Various studies have highlighted the paramount aspects of controller workload and its critical influence on operational safety in a complex airspace environment, based on factors such as cognitive processes and human error (Skorupski, 2017; Socha, 2020; Suárez et al., 2024).

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The high co-occurrence of safety-related keywords in this cluster highlights these aspects and their prevalence in ATM studies within the current context.

Within this cluster, the keywords used include aircraft collision, aviation safety, adequate information, cognitive load, and decision-making. The strong internal linkage among these terms indicates that research has consistently emphasised the safety-critical aspects of ATM. Many of these works focus on mitigating human error, enhancing situational awareness, and supporting air traffic controllers during high workload conditions.

Safety remains the primary pillar of ATM research, as human factors continue to influence operational performance.

4.2.2. Cluster 2 – Capacity and Airspace Efficiency

Results from Cluster 2 closely relate to the literature on capacity and efficiency focus discussed in Section 2.2.2 above. In literature, airspace sectoring, traffic flow management, and balancing demand and capacity are recognised as playing major roles in mitigating congestion and delay in high-density airspace environments (Dmochowski, 2017; Madhwal, 2017; Standfuss, 2024). The dominance of terms characteristic of airspace configuration and traffic characteristics in this cluster indicates that optimising capacity is a major concern for research in ATM environments that are under increasing demand pressure related to traffic volume.

This cluster is characterised by terms such as airspace sectoring, configuration, air traffic flow, pattern, and demand. These keywords represent research into the challenges posed by increasing traffic volume, sector capacity limitations, and the structural redesign of airspace. Various investigations aim to optimise sector configuration to reduce delays while balancing demand with available capacity. Since capacity constraints remain an important operational constraint, efficiency-focused research is essential (Martin et al., 2020).

4.2.3. Cluster 3 – Automation, Algorithms, and Digitalisation

The findings of Cluster 3 open up new avenues of discussion, which were initiated in Section 2.2.3. It has been proven in previous research that algorithmic models, machine learning, and data-driven decision support systems play a major role in traffic flow optimisation, accuracy improvement, and workload reduction in traffic centres (Torres, 2012; Standfuss, 2024; Jimenez, M. A., Tello, F., & Mateos, A. 2020). The density of computational/automation keywords in Cluster 3 verifies the widespread use of advanced technologies in efficiency-oriented ATM research.

The cluster is dominated by such keywords as algorithm, model, data, optimal solution, and new methodology. This categorisation mirrors the increasing trend toward computation-based methods, machine learning, data-driven operations, and automated decision-support tools. These works aim to enhance accuracy, reduce controller workload, and improve prediction and optimisation capabilities within ATM (Mirchi et al., 2015).

Automation is the transformative factor in ATM, increasingly shaping the design of the future operational system (Standfuss, 2024; Jakšić & Janić, 2020).

4.2.4. Cluster 4 – Trajectory-Based Operations and Operational Planning

This cluster includes terms like 2D graphical display, information, process, air operation, and aircraft skip.

Keywords include the optimisation of flight trajectories, conflict detection, route planning, and visualisation systems supporting controllers and pilots. These studies focus on improving airspace performance through better trajectory management.

Trajectory-based operations form a bridge between traditional air traffic control and emerging performance-based navigation concepts (Dmochowski, P. A. 2017).

4.2.5. Clusters 5 – Sustainability and Environmental Impact

The last cluster features words like SAF, or sustainable aviation fuel, emission, carbon price, fuel cost, and ATFM performance.

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This cluster highlights the increasing importance of environmental aspects in ATM research, particularly in light of stricter emission targets and higher expectations for the sustainability of the aviation sector. Sustainability has become a core research theme, pointing towards environmentally conscious ATM strategies (Mangav, D., McDermott, O., & Trubetskaya, A. 2026).

4.3. Central Keywords and Link Strength

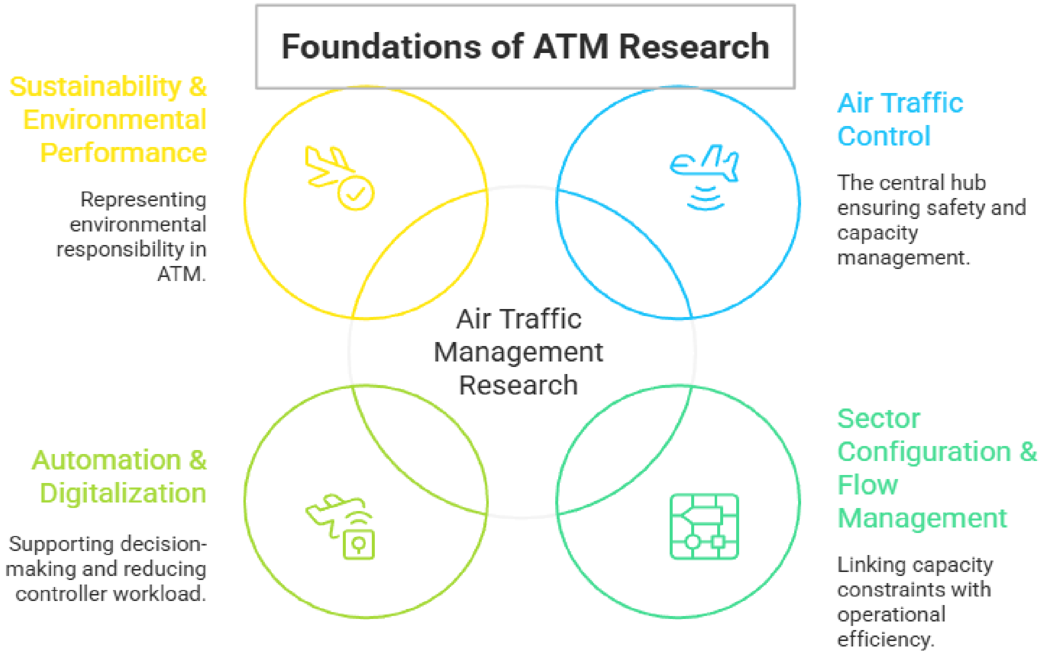

Figure 4. Visualisation of central keywords and their relationships in ATM research *(generated using napkin.ai)*

The following keywords serve as central hubs within the entire map, as indicated by the co-occurrence network. They are characterised by high link strength, since they frequently appear together with more clusters; thus, they bridge major research themes.

The most dominant keyword is "air traffic control", located near the centre of the network. Its strong links to the terms related to both safety and capacity suggest that it remains the core element of ATM research and operations (Dmochowski, 2017; Skorupski, 2017).

Additionally, "sector configuration" and "air traffic flow management" exhibit high centrality, linking capacity management to operational efficiency. These also often co-occur with topics such as delay, workload, and airspace structure, reflecting the system-wide importance of capacity balancing.

The core of the automation and digitalisation cluster is represented by keywords like "algorithm," "model," and "data"; their strong link strength suggests a growing research focus on computational methods, machine learning, and optimisation-based decision-support tools, which demonstrate the ongoing shift toward data-driven ATM operations.

Among the sustainable cluster, terms like "SAF," "emission," "fuel cost," and "carbon price" are highly internally connected. The fact that these terms are so closely related shows how environmental performance and policy-driven operations are increasingly being emphasised.

Overall, the central keywords suggest that four interacting forces have driven ATM research in the period 2014–2024:

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•operational safety,
•sector and capacity constraints,
•automation and digitalisation, and
•Sustainability requirements.

These hubs constitute the structural backbone of the ATM research landscape (Jakšić & Janić, Esteve & Zanin, 2025).

4.4. Density Map Interpretation

This density visualisation offers further insight into where research activity has been most focused within the ATM landscape. From this density map, regions in yellow correspond to a higher frequency of the keywords and stronger co-occurrence relationships, while areas in darker tints correspond to less frequently studied topics.

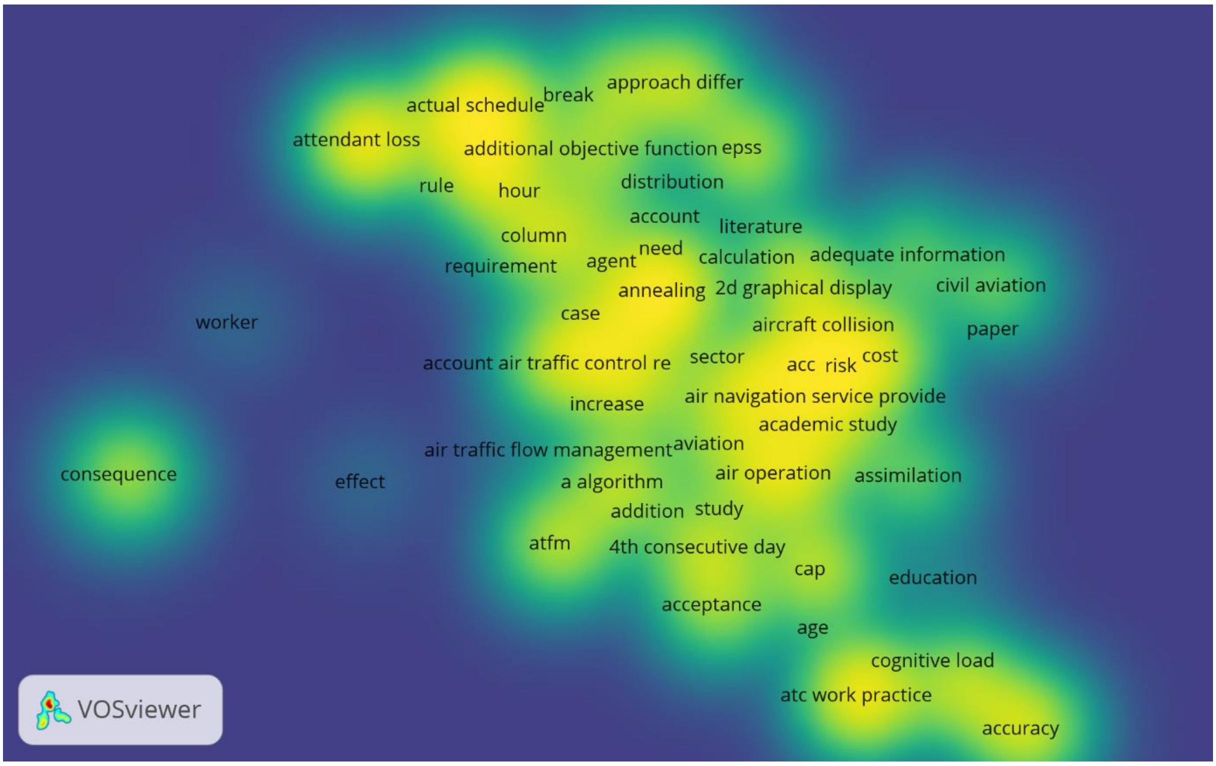

Figure 5. Density map of keyword co-occurrence in Air Traffic Management literature
(source: own compilation)

The brightest regions in the map correspond to keywords related to:
• air traffic flow / ATFM,
• airspace sectoring and configuration.
• Algorithmic and optimisation-based approaches, and
• safety-related concepts such as collision risk and information accuracy.

These areas emphasise the dominant research focus on managing traffic growth, sector efficiency, and the safety of increasingly complex operations.

Another catch is the high-density zone around keywords related to environmental performance, such as emissions, fuel costs, carbon prices, and SAF (Hamdan, 2022). This indicates that sustainability has become a major research priority, aligned with global environmental policies and the aviation industry's move towards greener operational strategies.

The density map reinforces the cluster analysis's observation that ATM research between the years 2014 and 2024 has concentrated on four major areas:
• operational safety,
• capacity and airspace efficiency,
• automation and digitalisation, and
• environmental sustainability. These dense regions represent the areas where ATM research has evolved over the last ten

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years and indicate the direction of scholarly attention.

5. Discussion

Table 2. Summary of the Five ATM Research Clusters

Cluster	Main Focus	Key Insight
Safety & Human Factors	Collision risk, workload, human performance	Safety remains the priority in ATM research
Capacity & Airspace Efficiency	Sectoring, ATFM, demand- capacity balance	Airspace efficiency is essential due to increasing traffic
Automation & Digitalization	Algorithms, ML, decision-support tools	Research trends indicate a clear shift toward data-driven ATMs.
Trajectory-Based Operations	Trajectory optimisation, conflict detection	Modern ATM shift toward performance-based operations
Sustainability & Environment	Emissions, SAF, carbon pricing	Environmental concerns increasingly shape ATM studies

(source: own compilation)

Specific findings from the keyword network and cluster analysis reveal that between 2014 and 2024, the dominant themes in ATM research centred on safety, capacity, automation, trajectory-based operations, and sustainability. The consistency of these themes in the literature, along with the trend from traditional ATC-focused studies toward more technology-driven and environmentally oriented research directions, is evident.

5.1. Safety and Human Factors

Safety is the most prominent theme identified within ATM. The interlinked nature of keywords such as "collision risk," "workload," "information accuracy," and "human performance" confirms previous conclusions drawn within the ATM body of knowledge (Skorupski, 2017; Socha, 2020), which states that the greatest influence on controller workload is, in fact, the density of air traffic. This confirms ATM safety-oriented research as the first pillar within ATM.

5.2. Capacity and Airspace Efficiency

Capacity and airspace efficiency are another essential area being researched in ATM. The way the keywords are grouped in the form of a cluster, with references related to airspace sectorization, traffic flow, and demand, signifies the ongoing attempt to reduce the effects of congestion and increasing volumes (Torres, 2012). In synchrony with earlier research efforts in this area, capacity limitations have been identified once again as a crucial barrier for ATM.

5.3. Automation and Digitalisation

The emphasis on keywords such as algorithms, data models, and decision support systems is indicative of the growing importance given to automation and digitalisation in modern ATM technology. It is in line with the overall digital evolution taking place in the aviation industry, with predictive analytics, machine learning, and optimisation increasingly being adopted to improve the accuracy of decisions and minimise the efforts of air traffic controllers. It is evident from the study that automation is emerging as a paradigm-shaping technology in future ATM systems (Jimenez, M. A., Tello, F., & Mateos, A. 2020; Standfuss, 2024; Dmochowski, 2017).

5.4. Trajectory-Based Operations

Trajectory-Based Operations are described by their strong focus on performance-driven ATM concepts. Trajectory-related keywords, focusing on planning, collision detection, and the predictability of operations, reflect a strong interest within the research community to address issues of delay, fuel burn, and airspace efficiency. These observations reinforce the sector's shift toward performance-driven navigation and flow management, highlighting Trajectory-Based Operations as key to Next Generation ATM Systems (Torres, 2012; Kistan, T., Gardi, A., Sabatini, R., Ramasamy, S., & Batuwangala, E. 2017; Jakšić & janić, 2020).

5.5. Sustainability and Environmental Impact

The increasing presence of sustainability-related terms, including emissions, sustainable aviation fuel, carbon pricing, and fuel costs, within the search data demonstrates that sustainability-related issues are becoming an increasingly integral part of ATM-related research. These findings are consistent with the global aviation plans to operate in a more environmentally sustainable manner. Sustainability-related matters are now increasingly being incorporated within the ATM-related research agenda, rather than being relegated to the margins (Hamdan, 2022; Jakšić & janić, 2020; Mangav, 2026).

5.6. General Interpret

On the whole, the evidence suggests a paradigm shift in the study of ATM, where the more traditional air traffic control-oriented paradigm is now being supplemented by, and in some cases, progressively supplanted by more technology-centric, performance-related, and environmentally sensitive paradigms. Safety and capacity remain, of course, the cornerstones, but the rising importance of automation, trajectory-related operations, and environmental considerations can only serve to underscore the primacy of new priorities in contemporary ATM. Nevertheless, the extension of the dataset to encompass 50 articles serves to support further this paradigm shift, where clearer patterns emerge regarding the relationship between safety, capacity, automation, and sustainability (Dmochowski, 2017; Jakšić & Janić, 2020; Esteve, P., & Zanin, M. 2025).

Table 3. Drivers and Barriers by Theme

Theme	Key Drivers	Key Barriers
Safety & Human Factors	Traffic density, operational complexity, resilience requirements	Cognitive load; human error; limited decision-support adoption
Capacity & Airspace Efficiency	Demand growth; network performance targets	Sector constraints, coordination overhead, and regulatory harmonisation
Automation & Digitalization	Data availability; ML/optimisation advances; performance-based ambitions	Certification/trust; interoperability; cyber-security risks
Trajectory-based Operations	Predictability; performance-based navigation; FOC-ATC integration	Legacy procedures; tooling maturity; cross-border coordination
Sustainability & Environment	Emission targets; carbon pricing; SAF initiatives	Measurement granularity; operational trade-offs; policy fragmentation

Source: Own compilation

6. Practical Implications

The findings of this study have significant implications for multiple stakeholder groups involved in the evolution of Air Traffic Management (ATM). Translating these insights into actionable strategies can accelerate the transition toward safer, more efficient, and environmentally sustainable airspace operations.

6.1. Regulators and Policy-makers

Regulators should align deployment roadmaps with measurable targets that simultaneously address safety, capacity, and environmental performance objectives. This alignment ensures that modernisation efforts do not prioritise one dimension at the expense of others. Furthermore, policy-makers need to incentivise data sharing and interoperability for automation tools by establishing robust standards and governance frameworks. Such measures will facilitate seamless integration of advanced technologies across jurisdictions. In addition, regulators should develop certification pathways for machine learning–enabled decision-support systems, specifying clear evidence requirements related to robustness, explainability, and latency. These pathways will help overcome trust and compliance barriers that currently hinder the adoption of AI-driven solutions.

6.2. Air Navigation Service Providers (ANSPs)

ANSPs should prioritise the implementation of trajectory-based operations that demonstrably reduce delays and fuel consumption while maintaining controller workload within acceptable limits. Investments in resilience—such as contingency procedures and cross-border coordination—must be informed by network-level analytics to ensure operational continuity under disruptive conditions. Moreover, ANSPs should establish human-in-the-loop evaluations for automation tools during trial phases. These evaluations will enable continuous monitoring of

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workload, situational awareness, and mode awareness, thereby mitigating risks associated with automation bias and unexpected system behaviours.

6.3. Technology Developers and Integrators

Technology developers must design interoperable, standards-compliant APIs and data models to facilitate integration with legacy ATM systems. Embedding human factors and explainability features into machine learning tools is crucial for fostering controller trust and encouraging adoption. Additionally, developers should provide uncertainty-aware optimisation capabilities that account for variables such as weather and demand fluctuations. These capabilities should be complemented by performance trade-off dashboards, enabling operational decision-makers to balance efficiency, safety, and sustainability objectives in real time.

6.4. Training and Human Factors

Training programs should be updated to incorporate modules on human–AI teaming, mode awareness, and strategies for mitigating automation bias. Scenario-based training exercises that expose controllers to varying traffic regimes and levels of automation will enhance adaptability and preparedness for future operational environments. Continuous monitoring of cognitive workload using validated measures should inform rostering decisions and the deployment of support tools. This proactive approach will help maintain controller performance and well-being in increasingly automated and data-driven ATM systems.

7. Conclusion

This paper conducted a bibliometric analysis of Air Traffic Management (ATM) from 2014 to 2024, aiming to highlight important themes and intersecting concepts within the body of knowledge. Utilising analysis software VOSviewer on keyword matrices reveals five critical groups of themes: safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability and the environment.

It is evident from the results that the backbone of ATM studies remains safety and capacity management. This highlights continued operational concerns regarding increased traffic density values. However, a trend is emerging towards automation, decision support systems based on data, and operational strategies based on trajectory, which indicate progress towards a performance-oriented ATM framework that employs technological support. Additionally, the emergence of sustainability topics suggests an increase in concerns and intentions related to the environment in current ATM studies.

From a scholarly perspective, this study makes several contributions by providing a clear roadmap of the shifts in ATM research topics over the last decade, with a clear linkage of relationships between these topics. From a practical perspective, this study presents concrete policy implications for policy-makers, air navigation service providers, and system developers by identifying key areas for shaping the future of ATM systems.

Nevertheless, the study also has certain limitations. The paper relied on a finite number of articles and presented a basic analysis of the mentioned keywords in the study, which may not be entirely accurate due to the conceptual and methodological divergences in the papers used. The next study could utilise a more extensive number of publications and employ multiple databases, in addition to using citation analysis to identify the themes of ATM papers. Another study could also observe the change in themes of ATM over a period of time to identify emerging themes.

The findings suggest a consensus that the current trend in ATM research is toward an integrated approach that balances safety, efficiency, technological innovation, and environmental sustainability. This holistic view will likely be crucial in the coming years for developing a resilient, efficient, and sustainable air traffic management system.

Through the expansion of the dataset and the strengthening of the keyword network, this research offers a more robust and comprehensive understanding of the ever-evolving paradigm of ATM research.

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Sovereign green bond reporting practices in the EU: A harmonised or a fragmented landscape?

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Abstract
In order to meet the growing funding needs of green transition in the European Union, member states started issuing green bonds. On the green bond market, sovereigns are expected to report on the use of the green bond proceeds and their impact. Several voluntary guidelines are available for green bond reporting on the market, including the International Capital Market Association Green Bond Principles (ICMA GBP) or the European Union Green Bond Standard (EuGBS), which is based on the EU Taxonomy. This study provides an overview on the current sovereign green bond reporting practices in the EU, taking into account their most recent green bond reports and related documents (green bond frameworks, external reviews etc.). The results show that all sovereigns in the EU implement the ICMA GBP, while many strive to comply with the criteria of the EU Taxonomy and EuGBS on a best effort basis. Due to the voluntary use of the standards, the reporting practices among sovereigns greatly vary: each country uses its own approach for EU Taxonomy assessment, allocation and impact reporting, which leads to market fragmentation and limited comparability of the sovereign green bonds. The EuGBS could create a common ground for reporting requirements by strengthening comparability and credibility and improving the transparency on the market. However, due to its strict requirements such as the alignment with the EU Taxonomy, it is complicated for sovereigns to comply with the standard.

Keywords
Sustainable finance, reporting, green bond, net zero

1. Introduction

Climate change, environmental degradation, biodiversity loss, drought are only some of the key challenges the world is facing these days (UN, 2025). Mitigating these challenges and ensuring a sustainable future is a key priority in the European Union (EU). The EU has signed and ratified the Paris Agreement and supports the UN Agenda 2030 for Sustainable Development (European Commission, 2025a; European Council, 2025a). It introduced the EU Green Deal with the long-term goal of becoming the world's first climate neutral continent by 2050 and announced the Fit for 55 package, aiming to reduce the EU's greenhouse gas emission at least by 55% compared with 1990 levels (European Commission, 2025b; European Council, 2025b). The EU is also creating strategies in order to protect the climate and environment. It published – among others – the EU Adaptation Strategy, which outlines a vision to become a climate-resilient society or the biodiversity strategy for 2030 to protect the nature and reserve the degradation of ecosystems (European Commission, 2025c, European Commission, 2025d).

Achieving the EU's ambitious commitments require an enormous amount of funding provided by both the private and public sector (Andersson et al., 2025). The role of the sovereigns is crucial, as they can incentivize investments, provide subsidies or state guarantees etc. The EU is providing funding for the member states, e.g. through the Recovery and Resilience Facility, the Common Agriculture Policy or the Cohesion policy for the 2021–2027 period, to support a greener, net zero-carbon economy (European Commission, 2025e; European Commission, 2025f; Christou et al., 2025).

Despite the support of the EU, the current amount of funding is not likely to be enough to reach the decarbonisation targets (Andersson et al., 2025). Therefore, many member states opt for raising funds by issuing green bonds. Green bonds are debt instruments supporting projects with environmental and sustainability aspects (Bécsi et al., 2022). On the green bond market, it is expected from the sovereigns to publish pre-issuance and post-issuance documents, including allocation and impact reports on the use of the green bond proceeds and their impact. Due to the lack of mandatory, binding regulations, reporting can lead to market fragmentation and data inconsistency (Manasses et al., 2022). This can effect the attractiveness of the green bonds and hamper the green bond issuance. In the Action Plan: Financing Sustainable Growth, the EU recognized the importance of establishing unified definitions and providing comparable information in sustainable finance

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(COM/2018/097). As a result, the Union created the EU Taxonomy, a unified classification system for sustainable activities and published the EU Green Bond Standard (EuGBS), a common framework for issuing green bonds in the EU (EU 2020/852; EU 2023/2631). These initiatives are primarily targeted at the private sector and the use of EuGBS still remains voluntary for green bond issuances. Therefore, fragmentation is expected to persist among sovereigns.

1.1. The green bond market in the EU

Since the first green bond was issued by the European Investment Bank (Climate Awareness Bond – CAB), the market has grown rapidly (Cortellini and Panetta, 2021). According to the International Capital Market Association (ICMA) Database, as of September 2025, the total outstanding amount of green bonds has almost reached USD 3,000 billion, of which sovereign green bonds account for approximately USD 500 billion (ICMA 2025a) (Figure 1).

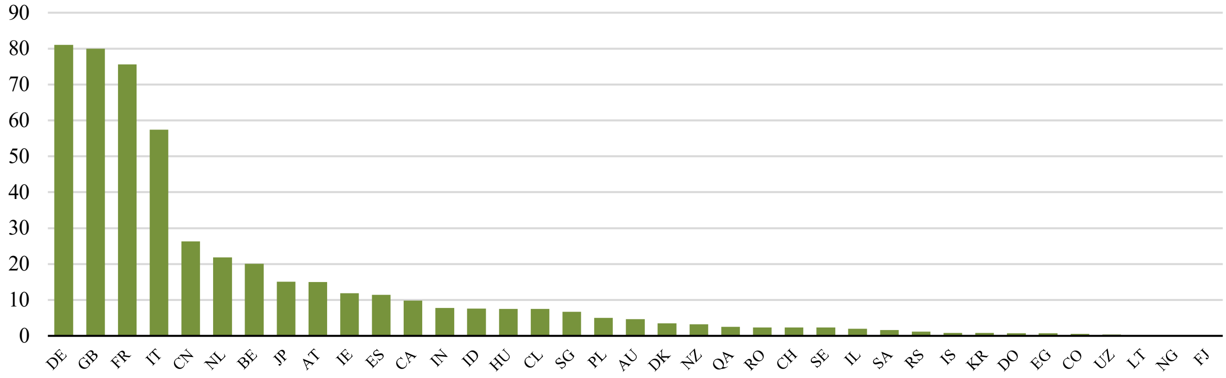

Figure 1. Global sovereign green bonds issuance (billion, as of September 2025)
Source: own editing based on ICMA (2025a)

In the EU, between 2014 and 2024, there have been a significant increase of green bond issuances by corporations and sovereigns, leading to a growing share of 0.1% to 6.9% in the total bond issuance. The share of sovereign green bonds in the total bonds issued also increased from 3.3% in 2020 to 4.2% in 2024. Sovereign green bond issuance is expected to continue, e.g. Hungary, Germany, Austria, Belgium also consider green bonds as a financing tool for reaching the climate targets in their National Energy and Climate Plans (European Environment Agency, 2025; European Commission, 2025g).

As of September 2025, 14 member states (Austria, Belgium, Denmark, France, Germany, Hungary, Ireland, Italy, Lithuania, the Netherlands, Poland, Romania, Spain, Sweden) have issued green bonds. As a result, at a global level, more than 60% of the outstanding amount of sovereign green bonds are from the EU member states, which also reflects the leadership of the EU on the green bond market (ICMA, 2025a).

1.2. Disclosures on the green bond market

On the green bond market, transparency and disclosure of information are essential. Investors rely on voluntary published pre-issuance documents (e.g. Green Bond Framework, EU Green Bond Factsheet) and post-issuance documents (e.g. green bond allocation and impact reports) or other materials (investor presentations, government policies, strategies). For example, to further improve the transparency and the communication with the investors in Hungary, the Government Debt Management Agency Private Company Limited by Shares (ÁKK) published a comprehensive Environmental, Social and Governance (ESG) profile document besides regularly publishing green bond reports. The material merges environmental, social and governance aspects and introduces the country's main ESG-related objectives, strategies, targets, challenges and achievements (ÁKK, 2025a). The role of external review providers is also significant, as they can enhance the credibility and consistency of the disclosed information by providing reviews and verification to ensure that issuers comply with best market practices and standards (Simeth, 2022).

Over the past few years, several voluntary guidelines and standards were published in order to improve the transparency of, strengthen investor confidence in and foster the issuance of green bonds. These include the ICMA Green Bond Principles (GBP) – which is currently the global standard for green bond issuances –, the Climate Bonds Standard from the Climate Bonds Initiative or the European Green Bond Standard (EuGBS), which defines the requirements for issuing the so-called "European Green Bond" (EuGB) by relying heavily on the EU Taxonomy Regulation (Brückbauer et al. 2023; Regulation

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(EU) 2020/852 and 2023/2631). As of September 2025, according to the ICMA database, 97% of the entire sustainable bond market is in alignment with the ICMA Principles.

The EU Taxonomy provides a classification system to define environmentally sustainable economic activities with regard to six environmental objectives. These objectives are: 1. Climate change mitigation 2. Climate change adaptation 3. The sustainable use and protection of water and marine resources 4. The transition to a circular economy 5. Pollution prevention and control 6. The protection and restoration of biodiversity and ecosystems. An economic activity is considered taxonomy-eligible if it has a description and a technical screening criteria set out in the Delegated Regulations of the EU Taxonomy. Current delegated regulations include: Climate Delegated Act – EU 2021/2139; EU 2022/1214; EU 2023/2485, Environmental Delegated Act – EU 2023/2486. An economic activity is taxonomy-aligned if it is taxonomy-eligible, fulfils the technical screening criteria in the relevant Delegated Regulation, and complies with the minimum safeguards criteria introduced in the EU Taxonomy Regulation. Under the technical screening criteria, the activity must contribute substantially to meeting at least one of the six environmental objectives (substantial contribution criteria – SC) while not causing harm in any of the other environmental objectives (do no significant harm criteria – DNSH) (Hummel and Bauernhofer, 2024; EU 2020/852).

Although, there are some similar features between the EuGBS and the ICMA GBP (both standards aim to regulate the use and the management of the green bond proceeds, the reporting practice etc.), significant differences between the two documents can also be observed (Table 1). First, the ICMA GBP is not based on any taxonomy, while the EuGBS relies on the EU Taxonomy. Second, the ICMA GBP recommends setting up a Green Bond Framework before the issuance, while the EuGBS requires issuers to publish the European Green Bond Factsheet. The ICMA GBP recommends an external reviewer to verify the Green Bond Framework and allocation reporting. In contrast with the ICMA GBP, the EuGBS requires an external reviewer, registered and supervised by ESMA (European Securities and Markets Authority), to verify the EU Green Bond Factsheet and the allocation report (Brückbauer, 2023; EU 2023/2631; ICMA, 2025b; ESMA, 2025).

In September 2025, Denmark became the first sovereign to issue a European Green Bond (Danmarks Nationalbank, 2025; Danish Ministry of Finance, 2025a). Apart from Denmark, the majority of the sovereigns in the EU issuing a green bond strive to implement the EU Taxonomy and the EuGBS on a best effort basis (Lukács and Bebes, 2025). Additionally, all member states apply the ICMA GBP, while for reporting purposes, some sovereigns also consider the ICMA's Handbook Harmonised Framework for Impact Reporting guideline (ICMA, 2024, henceforth ICMA Handbook).

As many sovereigns seek alignment with the EuGBS and the EU Taxonomy, and also adhere to the ICMA GBP while implementing elements from ICMA Handbook, the reporting practices and approaches greatly vary among sovereigns, which causes market fragmentation and hampers the comparability of sovereign green bonds. Therefore, understanding the market mechanisms and current disclosure practices is essential for the future development of the green bond market.

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Table 1. High-level comparison of the main elements of ICMA GBP June 2025 (latest updated version) and the EuGBS

Element	ICMA Green Bond Principles (version 2025)	EU Green Bond Standard 2025
Green Bond Framework/ EU Green Bond Factsheet	Pre-issuance, it is recommended to set up a Green Bond Framework. The framework demonstrates how the issuer aligns with the ICMA four core principles (Use of the Proceed, Process for Projects Evaluation and Selection, Management of Proceeds and Reporting) and introduces the issuer's overarching sustainability strategy.	Pre-issuance, it is required to fill and publish the EU Green Bond Factsheet, using the specific template in the standard. On the factsheet, several types of information need to be disclosed, including how the bond will contribute to the issuer's environmental strategy, the intended allocation of bond proceeds, allocation to taxonomy-aligned activities, estimated impact, process and timeline for allocation, information on reporting etc.
Use of Proceeds	The green bond proceeds should be used for projects promoting environmental benefits. An indicative list of project categories[1] is showcased in the GBP. The principles do not require the use of any taxonomy or threshold criteria, allowing a broader space for financing.	Green bond proceeds must be aligned with the EU Taxonomy and the relevant technical screening criteria. The so-called flexibility pocket allows an allocation up to 15% of proceeds to activities not aligned with the technical screening criteria.[2]
Reporting	The issuer should report on the use of proceeds annually until full allocation. The report should include a list of projects, the amount and their expected impact. It is recommended to use the ICMA Handbook, which outlines sector specific guidance and reporting metrics.	Issuers must prepare and publish allocation reports for every 12-month period (beginning on the issue date) until full allocation of proceeds. The allocation report must be made public within 270 days of the end of each 12-month period. The issuer must produce an impact report after the full allocation of the proceeds (or at least once during the lifetime of the bond). For allocation and impact reporting, the standard provides templates.
External Review	Pre-issuance (framework) and post-issuance (allocation) review is recommended. Pre-issuance: the Green Bond Framework alignment with the Green Bond Principle's components should be reviewed. Post-issuance: recommended to use an external auditor or third party to verify internal tracking and allocation of the funds.	Pre-issuance (factsheet) and post-issuance (allocation report) review by an external reviewer is mandatory, impact report review is recommended. Sovereigns have two options to receive a post-issuance review: 1. from an external reviewer, 2. from an external reviewer and a State auditor.[3]

Source: own editing based on ICMA (2025b), EU 2023/2631, Clifford Chance (2023)

2. Data and methods

The article provides a comprehensive overview on the recent sovereign green bond reporting practices in the EU by highlighting key areas: the EU Taxonomy assessment, allocation and impact reporting and external review received on the reports. Since the study focuses on the current reporting practices and related disclosures, publicly available documents published between January 2024 and December 2025 were taken into account. As a result, documents from the following countries were analysed: Austria, Belgium, Denmark, France, Germany, Hungary, Ireland, Italy, Spain, the Netherlands and Romania.

Several disclosures have been reviewed, including green bond reports and additional documents complementing the reports such as green bond frameworks, Excel files (the summary of the studied materials is in Appendix 1, Table 4). Note that in some cases it was difficult to interpret the EU Taxonomy assessment and/or the allocation and impact reports due to ambiguous definitions, wording and incoherent data.

3. Results and discussion

The European Union has established the EU Taxonomy as a classification system to define environmentally sustainable economic activities, forming the backbone of its sustainable finance framework. This taxonomy underpins the EU Green Bond Standard (EuGBS), which sets voluntary guidelines for green bond issuance and reporting. EU Taxonomy assessment involves determining the eligibility and alignment of financed activities with technical screening criteria, minimum safeguards, and "do no significant harm" principles across six environmental objectives. Reporting under this framework aims to enhance transparency and comparability by requiring issuers to disclose allocation and impact data, often complemented by external reviews. Despite these efforts, current practices among sovereign issuers remain fragmented, as alignment with the EU Taxonomy and EuGBS is largely voluntary, leading to diverse methodologies and limited harmonization across member states.

[1] Renewable energy; energy efficiency; pollution prevention and control; environmentally sustainable management of living natural resources and land use; terrestrial and aquatic biodiversity; clean transportation; sustainable water and wastewater management; climate change adaptation; circular economy adapted products, production technologies and processes and green buildings.

[2] These activities might include: 1. economic activities where technical screening criteria is not available (these need to meet, where applicable, the generic criteria for 'do no significant harm' set out in the Taxonomy Regulation (EU 2021/2139); 2. activities in the context of international support reported in accordance with internationally agreed guidelines.

[3] In the case of the second option, the State auditor's task shall be limited to review the allocation of the bonds proceeds while the external reviewer shall verify the taxonomy-alignment of the expenditures.

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3.1. EU Taxonomy assessment

While sovereigns are not obliged to report on the eligibility and alignment of their expenditures with the EU Taxonomy, as a response to the market developments and the increasing expectations of the investors, many sovereigns started integrating elements from the taxonomy (EU 2021/2178). From September 2025, Denmark will adhere to the EU Green Bond Standard, while also align with the ICMA GBP. According to the country's EU Green Bond Factsheet, the green bond proceeds will be allocated exclusively to taxonomy-aligned activities (Danish Ministry of Finance, 2025a).

Although the other EU countries have not published an EU Green Bond Factsheet yet, the findings show that most of them seek alignment with the EU Taxonomy on a best effort basis, for example by mapping their eligible green expenditures to the 6 objectives of the EU Taxonomy. Some sovereigns also assess their green expenditures considering the EU Taxonomy technical screening (substantial contribution, do no significant harm) and minimum safeguards criteria. These countries strive to showcase the eligibility and alignment of their expenditures in their Green Bond Framework and/or green bond reports (Table 2). Each country has its own approach for showcasing taxonomy-alignment, which limits comparability.

Table 2. Examples of the EU Taxonomy assessment practices in the EU (cc = country code)

CC	High level summary of the assessment practice
NL	12 economic activities were identified and analysed by Moody's, of which eleven was found to be aligned with the EU Taxonomy under the Climate and Environmental Delegated Act (EU 2021/2139; EU 2023/2486). In the green bond report, the country does not visualise the share of green bond expenditures aligning with the EU Taxonomy, although it confirms that the allocated expenditures are aligned with the substantial contribution criteria and do no significant harm criteria except for one activity, which is the tax relief and subsidies for electric and plug-in hybrid electric vehicles (Dutch State Treasury Agency, 2023, 2025a; Moody's Ratings, 2025).
BE	When updating the Green Bond Framework in 2022, Moody's assessed the eligible expenditures of the country. Two taxonomy activities related to railway were identified and deemed to be aligned with the Climate Delegated Act (EU 2021/2139) in force at the time of assessment. In the green bond report, the country allocates the majority of its green bond proceeds to these taxonomy-aligned railway activities. Belgium also examines the taxonomy-eligibility of expenditures not assessed by Moody's at the time of updating the framework. Overall, in the green bond report, the country displays the share of taxonomy-aligned, taxonomy-eligible and non-verifiable expenditures (Belgian Debt Agency, 2022, 2025a; Moody's ESG Solutions, 2022).
HU	When Hungary was updating its Green Bond Framework, Morningstar Sustainalytics assessed the technical screening criteria for several activities under the Climate Delegated Act (EU 2021/2139). According to the country's latest report, it reassesses the available expenditures during the reporting period based on all the current Delegated Acts (Environmental Delegated Act – EU 2023/2486 and Delegated Acts amending the Climate Delegated Act – EU 2022/1214, EU 2023/2485). First, the taxonomy-eligibility of the expenditures was identified. In case of eligibility, as a next step, the country assesses the alignment of the expenditures with the technical screening criteria of the Delegated Acts. This exercise is based on interviews, consultations with the ministries, beneficiaries and EU Taxonomy questionnaires. In the report, the sovereign dedicates a separate EU Taxonomy assessment section with a detailed breakdown of the expenditures and the results of the assessment. The country also provides an overview on the share of taxonomy-aligned and partially-aligned (fulfilling the substantial contribution criteria, but not or partially fulfilling the do no significant harm criteria) expenditures and a case study to demonstrate its assessment approach (ÁKK, 2023, 2025b; Morningstar Sustainalytics, 2023).
FR	Although France's latest green bond report (published in 2025) is based on the country's Green Bond Framework 2017 (which did not incorporate the EU Taxonomy, since there was no taxonomy regulation at that time), the country conducts an EU Taxonomy assessment and displays the share of taxonomy-eligible, non-eligible and not analysed expenditures. Furthermore, the country breaks down the taxonomy-eligible expenditures, showcasing the share of expenditures fulfilling the substantial contribution and do no significant harm criteria. The country also presents some case studies on the selected expenditures, summarising the taxonomy assessment results (Agence France Trésor, 2025a). In its updated Green Bond Framework (published in 2025), the country obliges itself to continue the taxonomy assessment process and display the results in each upcoming green bond report. According to the updated Framework, the country will also publish an ad hoc document with a detailed mapping of environmental, social laws and regulations in force in the country and the internal processes to meet the do no significant harm and minimum social safeguards criteria set out in the Delegated Acts (Agence France Trésor, 2025b).
IT	The country has a specific, detailed process in place to assess the allocated expenditures in the green bond report. The assessment is based on the COFOG (classification of the functions of government), ISIC (International Standard Industrial Classifications), NACE Rev.2 and Taxonomy Compass (Ministero dell'Economia e delle Finanze, 2025a). In the updated Green Bond Framework (published in 2025), the country commits to aligning certain activities with the substantial contribution criteria under the Climate and Environmental Delegated Act (EU 2021/2139; EU 2023/2486), meanwhile also considering the DNSH criteria where feasible. The framework also highlights, that in the upcoming green bond reports a section will be dedicated to the EU Taxonomy (Ministero dell'Economia e delle Finanze, 2025b).
ES	In the latest green bond report, the country provides qualitative information on the EU Taxonomy alignment of certain expenditures. For expenditures under clean transport category, according to the country, the selection criteria takes into account the technical screening criteria related to climate change mitigation objective defined in the EU Taxonomy on a certain level. However, information on the assessment process for such projects is not available in the report. As for the expenditures related to agricultural insurance, Spain describes the expenditure's alignment with the "Non-life insurance: insurance against climate-related risks" taxonomy activity (Tesoro Público, 2025).

Source: own editing based on the sovereigns' most recent Green Bond Reports and related materials such as Green Bond Framework, External Reviews

Some countries like Romania do not provide information on the taxonomy-alignment of green expenditures in the reporting but integrate certain elements from the regulation. For example, according to the criteria of the Clean Transportation project category under the country's Green Bond Framework, until the end of 2025, low-carbon passenger

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vehicles with a tailpipe emissions intensity of maximum 50 g CO_2/km, from 2026 onwards, only vehicles with emissions intensity of 0 g CO_2/km are eligible for financing. This criteria is adopted from the technical screening criteria of the EU Taxonomy's Climate Delegated Act (Government of Romania, 2023; EU 2021/2139).

In many cases, the misuse of wording, phrasing and inconsistency in the documents (Green Bond Framework, external review, green bond report) can potentially lead to a misunderstanding and an assumption on what extent the issuer aligns with the taxonomy, how the taxonomy assessment is executed and which Delegated Acts and technical screening criteria the issuer considers for the taxonomy assessment. These include wording such as "eligible to be Taxonomy-aligned", "likely aligned", "likely partly aligned", "potentially environmentally sustainable sectors, in line with the objectives of the EU Taxonomy". This practice also demonstrates how diversified the market is when it comes to EU Taxonomy assessment.

3.2. Reporting

Both the ICMA GBP and EuGBS require issuers to report on the allocation and impact of the green bond proceeds after the issuance. While the EuGBS contains separate allocation and impact reporting templates that are mandatory to use, the ICMA GBP does not include any templates for reporting purposes. Instead, the ICMA GBP recommends adopting the ICMA Handbook, which outlines core principles, recommendations, while providing sector specific guidance, reporting metrics and templates for impact reporting (ICMA, 2024, 2025b; Regulation (EU) 2023/2631). Since the latest green bond reports published by sovereigns are based on ICMA GBP, issuers had more freedom in creating their own reporting structure, having unique approaches for designing and highlighting certain content.

The findings show that some countries (Austria, Belgium, France, Hungary, Italy, the Netherlands) publish an integrated report, which combines the allocation and impact of the green bond proceeds. It must be noted that France's annual green bond report contains both allocation data and performance indicators (indicators, which are used for the state's budgetary procedure) Meanwhile other countries (Denmark, Germany, Ireland, Romania, Spain) publish allocation and impact reports separately. In general, allocation reports are published annually (until the full allocation of green bond proceeds) followed by an impact report with a time lag. The only exception is Spain, since the country discloses the allocation and impact report at the same time.

Publishing an integrated report may increase the transparency and clarity, as all information is available in one document, the connections and synergies between the allocation and the impact are clearly outlined. Since all the information is disclosed related to the projects, investors do not have to wait months or years for an impact report to be published. On the other hand, publishing the impact report following the allocation report allows more time for sovereigns for developing the content of the report and display the project's achieved impact – which might not be available or measurable at the time of the allocation. Overall, the choice of the reporting structure, the publication date of the allocation and impact report might depend on the investors' preferences, the country's capacities, the data availability of the projects or the management related to the state budget and final accounting process.

It is worth mentioning that some sovereigns like Belgium, the Netherlands, Ireland, Austria and Romania also publish additional documents, such as Excel files together with the green bond report. These Excel files summarise the allocation and/or impact data or even complement the green bond report with additional data. For example, Romania published an Excel document as an Annex to its green bond allocation report, where it details the name of the projects, their brief description, location, beneficiaries and allocated amount (Romanian Ministry of Finance, 2025). In the Austria's Green Investor Report Spreadsheet 2024 Excel document, the country provides all the allocation and impact data, a detailed overview of the green expenditures from the latest green bond report as well as historical data regarding the green bond issuances (OeBFA Austria Treasury, 2025).

In France, the Green OATs Evaluation Council is an independent body that was set up in 2017 with internationally recognised experts. The council is mandated to analyse the impact of the selected green expenditures financed by the country's green bond. Since 2017, evaluation reports are published annually and separately from the country's green bond reports. The results of these evaluation reports are highlighted in France's annual green bond reports (Agence France Trésor, 2025a).

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3.2.1. Allocation Reporting

The ICMA GBP provides an indicative project category list for eligible green expenditures. The EuGBS does not include a similar categorization to the ICMA GBP, but obliges issuers to display the share of the taxonomy-aligned expenditures and economic activities listed in the Delegated Regulations (e.g. afforestation, infrastructure for rail transport, construction of new buildings) on the Green Bond Factsheet and reporting templates (ICMA, 2025b; EU 2023/2631).

The findings show that issuers take into account the indicative project categories from the ICMA GBP in their Green Bond Framework and green bond reporting. While some sovereigns use the same project categories from the ICMA GBP, others modify the titles or even create new ones. The study also reveals that each sovereign allocated most of its green bond proceeds to projects under the Transport/Clean Transportation category, except for Romania and France (Table 3). While Romania allocated the majority of the proceeds to projects under the "Sustainable Water and Wastewater Management" category (projects related to the construction of water supply and wastewater infrastructure), France used most of the green bond funds on the "Multi-sector" category, which relates essentially to research funding covering several economic sectors.

Table 3. Top three allocation category in the latest sovereign green bond reports (cc = country code)

CC	Green category with the highest allocation	Share in total allocation (%)	Green category with the second highest allocation	Share in total allocation (%)	Green category with the third highest allocation	Share in total allocation (%)
AU	Clean transportation	**58.8%**	Renewable Energy	**16.9%**	Energy Efficiency	**8.6%**
BE	Clean transportation	**87.4%**	Living Resources and Land Use	**7.0%**	Renewable Energy	**2.7%**
DE	Transport	**50.7%**	International cooperation	**22.1%**	Energy and industry	**13.4%**
DK	Clean transportation	**93.8%**	Renewable energy	**6.2%**	-	
ES	Clean transport	**67.5%**	Sustainable water and wastewater management	**20.0%**	Adaptation to climate change	**12.5%**
FR	Multi-sector	**26.3%**	Energy	**20.3%**	Building	**19.1%**
HU	Clean transportation	**89.2%**	Land use & living natural resources	**9.7%**	Pollution prevention & control	**0.6%**
IE	Clean transportation	**57.7%**	Sustainable water and wastewater management	**29.1%**	Environmentally Sustainable Management of Living Natural Resources and Land Use	**6.2%**
IT	Transport	**40.5%**	Energy efficiency	**34.9%**	Protection of the environment and biological diversity	**9.1%**
NL	Clean Transportation	**51.0%**	Renewable energy	**28.7%**	Climate Change Adaptation & Sustainable Water Management	**20.3%**
RO	Sustainable Water and Wastewater Management	**42.5%**	Ecologically sustainable management of living natural resources and land use	**21.5%**	Climate change adaptation	**18.8%**

Source: own editing based on the sovereigns' most recent Green Bond Reports

Under the Transport/Clean Transportation category, a significant amount of the funds were allocated to projects related to railway infrastructure and operation, while proceeds were also used for supporting low or zero-carbon transport (e.g. hybrid cars, pure electric vehicles), public transport (including bus, metro etc.), cycling or waterway freight. In the EU, usually the state owns the national railway company and is responsible for its operation and maintenance, which may be one of the reasons behind the high allocation towards railway (Bulková et al., 2024). Another motive can be that the transport sector is one of the highest greenhouse gas (GHG) emitters among the sovereigns – according to the latest EU Climate Action Progress Reports (European Commission, 2025h). Therefore, operating and maintaining the railways can encourage the modal shift from road to a more sustainable transport, lowering the GHG emissions of the country, especially if the railway is electrified (European Commission, 2025h). For example, when it comes to railway allocation, Hungary supports only the electrified railway network with the green bond proceeds (ÁKK, 2025b).

3.2.2. Impact reporting

Both the EuGBS and ICMA Handbook expects issuers to report on the environmental impact and the related methodology behind the evaluation (ICMA, 2024, EUR-Lex, 2023). Since projects may have other sustainability impact too, the two guidelines also encourage to disclose the social benefits of the projects. Although there are similar elements in the EuGBS and ICMA Handbook, the overall requirements are different. For example the ICMA Handbook recommends to report on the estimated lifetime results of the projects or the project's economic life (in years), while the EuGBS requires to showcase

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an estimate of the project's adverse (negative) environmental impact. The ICMA Handbook includes a list of indicators (core, other, other sustainability) under each green sector and recommends to report on at least a limited number of sector specific core indicators, while the EuGBS does not contain a list of indicators that could be used by the issuers (ICMA, 2024; EU 2023/2631).

Since sovereigns are not restricted to use specific indicators for reporting, the impact indicators showcased in the green bond reports greatly vary among sovereigns. Based on the findings, each country discloses environmental impact indicators in their green bond report. The reduced/avoided greenhouse gas emission appears to be the most widely used indicator, followed by other commonly used indicators like the production of renewable energy (or energy generated from renewable sources) and energy saved. Besides impact indicators, outcome or output indicators are also reported. For example for railway transport, the length of railway lines renovated/maintained/electrified or the passenger kilometres are often presented.

For calculating the impact of certain projects, several methodologies are available (both nationally and globally). The findings show that sovereigns use different methodologies, which may not be consistent and comparable with each other. Therefore, providing a detailed description of the methodology and the evaluation is crucial. Most sovereigns include a methodology chapter or Annex in their green bond report, where information is provided on the calculation behind the impact numbers. Sovereigns like Germany also highlight the assumptions and limitations considered for calculating the impact (Federal Ministry of Finance, 2024). Belgium also publishes a methodology annex together with the green bond report, presenting the impact methodologies in details and with flowcharts (Belgian Debt Agency, 2025b).

Some sovereigns also report on other type of sustainability indicators (e.g. social, socio-economic, adverse), although it is not a common practice in the EU. The Netherlands includes a brief social indicator section in its green bond report, where information is provided on three selected social indicators: rail mobility, people protected by flood defence work and grid availability. The country also presents two adverse indicators: the use of space by offshore wind parks (in square kilometres) and the noise pollution of rail traffic (reference points, where noise level exceeded the maximum allowed limit) (Dutch State Treasury Agency, 2025a). Hungary presents the low-carbon GDP and low-carbon employment effect of the expenditures based on a model developed by ÁKK and also highlights the social co-benefit of relevant projects (ÁKK, 2025b). Italy calculates the socio-economic impact of the projects, based on the so-called SAM (Social Accountability Matrix) model. This way, the country is able to showcase the contribution of the financed projects to the GDP growth (induced Gross Domestic Product) and their impact on labour demand (as workers needs to meet induced production) (Ministero dell'Economia e delle Finanze, 2025a).

It is important to note, that impact of certain projects can occur during their entire lifetime (energy efficiency renovation, installation of renewable energy capacities such as solar panels, the upgrade or electrification of railway lines etc.). Where possible, sovereigns strive to disclose the accumulated impact over the lifespan of the financed projects (lifetime impact). Hungary reports on the GHG emissions avoidance of metro M3 reconstruction with the expected lifetime of 30 years based on a climate benefit analysis prepared for the project (ÁKK, 2025b). Italy presents the GHG savings over the entire lifetime of the financed interventions using the CO_2mpare Evolution model and also takes into account external studies relating to the useful life of the projects (lifetime ranges from a minimum of 27 years to maximum 37 years) (Ministero dell'Economia e delle Finanze, 2025a). Germany applies an eight-year lifetime for calculating the impact of energy efficiency projects in industry and businesses (Federal Ministry of Finance, 2024). For evaluating the GHG emission avoidance, Belgium considers a 45 years lifetime of the purchased rolling stock, and a 40 years lifetime for railway maintenance investment (Belgian Debt Agency, 2025a). Denmark considers the accumulated CO_2 emission avoidance for a 15-year lifespan of the financed zero- and low-emissions vehicles (Danish Ministry of Finance, 2025b).

3.3. External Review

The role of external reviewers is significant on the market as they provide independent review on pre-issuance (Green Bond Framework, EU Green Bond Factsheet) and post-issuance documents (green bond reports), boosting the credibility and transparency on the market. Currently, there are several service providers including Morningstar Sustainalytics, Moody's Ratings, ISS-Corporate, S&P Global Shades of Green, Sustainable Fitch etc. that issue external reviews. There are also service providers, offering external audit and limited assurance services like KPMG or Deloitte on the verification of the green bond allocation. According to the EuGBS, only external reviewers registered by the ESMA will be able to provide an

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external review on the EU Green Bond documents (registration required form 1 January 2026), meanwhile the ICMA GBP does not define any requirement for external review providers (ESMA, 2025; ICMA 2025b).

Despite being only recommended by the ICMA GBP, all member states received at least one type of an external review on their green bond reports (Figure 2).

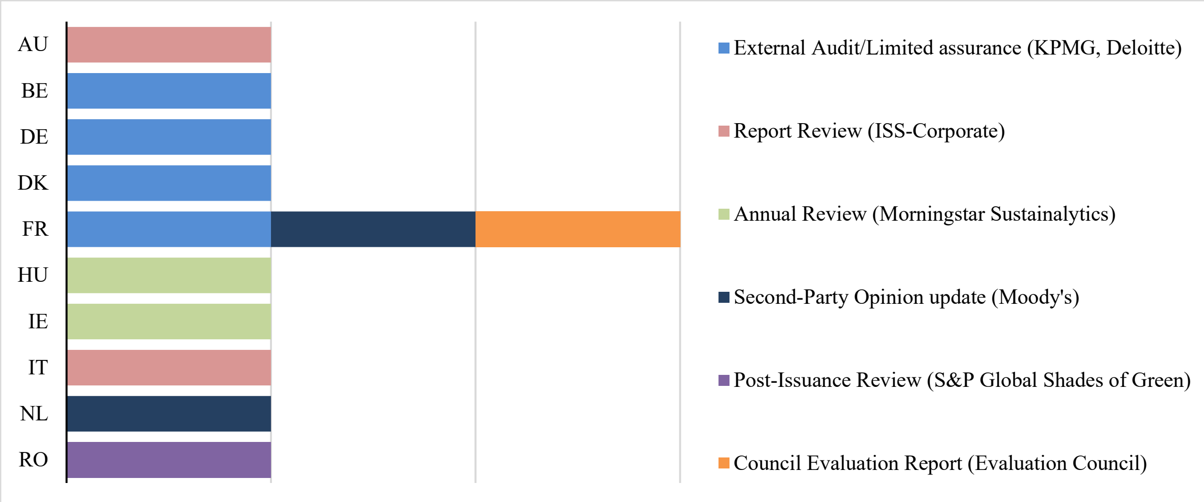

Figure 2. External Reviews provided for the most recent Green Bond Reports published by the sovereigns (cc = country code)
Source: own editing based on the sovereigns' most recent Green Bond Reports and External Reviews
Note: State audit is not indicated on the Figure.

For post-issuance review, countries engage several external reviewers, who apply different approaches and methodologies when providing an opinion on the reports. Some countries opt for an external audit/limited assurance service. There are countries also highlighting that their allocation is verified by state audit. For example, the Netherlands notes that the Central Government Audit Service (Auditdienst Rijk) has also audited the allocation in its latest green bond report (Dutch State Treasury Agency, 2025b). Spain's allocation report is verified by the General Comptroller of the State Administration (Oficina Nacional de Auditoría, 2025). In France, the Council Evaluation Reports can also be considered as a form of an external review, since the Green OATs Evaluation Council is an independent body and provides detailed analyses on the quality of the eligible green expenditures (Agence France Trésor, 2025a).

4. Conclusion

To reach the sustainability goals of the EU, a substantial amount of funding is required. Sovereigns play a crucial role in financing the green transition and building a sustainable future. Besides receiving EU funding for the aforementioned purposes, sovereigns also choose alternative ways to raise funds, for example by issuing green bonds. Currently, the issuance of the green bonds is regulated by voluntary standards and principles, such as the ICMA GBP, the ICMA Handbook or the EuGBS, which is based on the EU Taxonomy.

In order to be credible and transparent, issuers are expected to integrate the voluntary standards and principles for green bond issuances and reporting. In the EU, each of the member states use the ICMA GBP, while some countries also take into account elements from the ICMA Handbook. Additionally, sovereigns started to seek alignment on a best effort basis with the EuGBS and the EU Taxonomy. So far, Denmark is the only country in the EU that published the EU Green Bond Factsheet and issued an European Green Bond.

The study provides an overview on the green bond reporting practices in the EU based on the recent sovereign green bond reports and related disclosures. The article focuses on three key areas: EU Taxonomy assessment, allocation and impact reporting, and external verification practices.

An increasing number of countries started to assess their green expenditures based on the EU Taxonomy, presenting their taxonomy-alignment in the Green Bond Framework and/or green bond report. The taxonomy assessment practice used by sovereigns is different, with each country applying its own methodology and approach. Some countries do not assess the expenditures, but implement some elements – such as threshold criteria – form the taxonomy in their Green Bond

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Framework. Sometimes, it is not possible to determine on what extent the issuer aligns with the EU Taxonomy due to the ambiguous wording, the lack of details or the inconsistent information between the Green Bond Framework, the green bond report and an external review.

Many sovereigns publish an integrated report, which combines the allocation and impact data, while others publish a separate allocation and impact report. Some sovereigns also issue other documents together with the green bond reports in the form of Excel files. As for the allocation of the green bond proceeds, in general, the Clean Transportation/Transport goal is the most allocated green bond category with railway receiving a significant amount of the funds. Regarding impact reporting, the GHG emission avoidance is the most commonly used indicator, while the use of other type of sustainability indicators such as social, socio-economic or adverse indicators is not common.

While the ICMA GBP only recommends, the EuGBS requires issuers to engage an external reviewer in order to provide a review on the pre-issuance and post-issuance documents. All the analysed sovereigns received at least one type of an external review on their green bond report from third parties or audit service providers. These practices boost the transparency and the credibility of the disclosed information and seek alignment with the EuGBS.

The article demonstrates that fragmentation still remains a challenge on the green bond market as sovereigns use multiple voluntary documents for reporting. Each of the latest green bond reports analysed in the article has its own structure, content, design, methodologies for allocation, impact and EU Taxonomy assessment, therefore comparability is limited. The EU recognised that the absence of common standards, the diverging measures and approaches can lead to market fragmentation, uneven market conditions, limited comparability and hinder the fundraising for sustainability purposes. Therefore, the EU established the voluntary EuGBS, which regulates the green bond issuance, the reporting practice and ensures that external reviewers are registered and supervised by ESMA. The creation of a common and reliable label can build trust and help to channel more investment into green finance.

Despite these initiatives, issuing sovereign European Green Bonds as a common practice in the EU is hardly expected within a reasonable time, due to the voluntary use of the principles and standards. Another reason is that the EU Taxonomy is primarily designed for the private sector without considering some of the specific features and scopes of public financing. Some sectors being crucial for sovereigns in the green transition – such as agriculture – are not covered by the EU Taxonomy, creating a barrier for aligning certain expenditures.

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Appendix

Table 4. Documents reviewed for the Results and Discussion (section 3) (cc = country code)

CC	Green Bond Framework (GBF) or EU Green Bond Factsheet (EUF) and publication year	Pre-issuance review on the Framework/ Factsheet (yes/no)	Latest Green Bond Report (A = Allocation, I = Impact, IN = Integrated) and publication year	Post-issuance review on the report[1] (yes/no)	Other documents related to post-issuance[2] (yes/no)	Website
INCLUDED IN THE ANALYSES: countries that published a green bond report between January 2024 – December 2025						
AU	GBF – 2022	Yes	IN – 2025	Yes	Yes	https://www.oebfa.at/en/financing-instruments/green-securities.html
BE	GBF – 2022	Yes	IN – 2025	Yes	Yes	https://www.debtagency.be/en/green-olo
DE	GBF – 2020	Yes	A – 2025 I – 2024	Yes	No	https://www.deutsche-finanzagentur.de/en/federal-securities/types-of-federal-securities/green-federal-securities
DK	GBF – 2021 EUGBF - 2025	Yes	A – 2024 I – 2025	Yes	Yes	https://www.nationalbanken.dk/en/government-debt/funding-strategy/green-bonds
ES	GBF – 2021	Yes	A – 2025 I – 2025	Yes	No	https://www.tesoro.es/en/deuda-publica/el-programa-de-bonos-verdes-soberanos https://www.tesoro.es/en/deuda-publica/informacion-para-inversores
FR	GBF – 2017 GBF – 2025	Yes	IN – 2025	Yes	Yes	https://www.aft.gouv.fr/en/framework-and-second-party-opinion https://www.aft.gouv.fr/en/allocation-and-performance-report
HU	GBF – 2023	Yes	IN – 2025	Yes	No	https://www.akk.hu/green-bond/green-bondFramework-2023-en
IE	GBF – 2018	Yes	A – 2025 I – 2025	Yes	Yes	https://www.ntma.ie/business-areas/funding-and-debt-management/government-securities/irish-sovereign-green-bond-documents
IT	GBF – 2021 GBF – 2025	Yes	IN – 2025	Yes	Yes	https://www.dt.mef.gov.it/en/debito_pubblico/titoli_di_stato/quali_sono_titoli/btp_green/#car3 https://www.dt.mef.gov.it/en/debito_pubblico/emissioni_titoli_di_stato_interni/comunicazioni_emissioni_btp_green/post_emissioni/
NL	GBF – 2023	Yes	IN - 2025	Yes	Yes	https://english.dsta.nl/subjects/g/green-bonds
RO	GBF – 2023	Yes	A – 2025 I – not published yet	Yes	Yes	https://mfinante.gov.ro/en/web/trezor/obligatiuni-verzi
EXCLUDED FROM THE ANALYSES: countries that did not publish a green bond report after January 2024						
LT	GBF – 2018	Yes	IN – 2023	No	No	https://finmin.lrv.lt/en/competence-areas/state-debt-management/government-securities/government-securities-auctions/green-bonds/
PL	GBF – 2016 GBF – 2025	Yes	IN – 2022	Yes	No	https://www.gov.pl/web/finance/issues-international-bonds
SE	GBF – 2020	Yes	IN – 2021	No	No	https://www.riksgalden.se/en/our-operations/central-government-borrowing/issuance/green-bonds/

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EU 2020/852 – Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088. URL: http://data.europa.eu/eli/reg/2020/852/oj

EU 2021/2139 – Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives. URL: http://data.europa.eu/eli/reg_del/2021/2139/oj

EU 2021/2178 – Commission Delegated Regulation (EU) 2021/2178 of 6 July 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by specifying the content and presentation of information to be disclosed by undertakings subject to Articles 19a or 29a of Directive 2013/34/EU concerning environmentally sustainable economic activities, and specifying the methodology to comply with that disclosure obligation. URL: http://data.europa.eu/eli/reg_del/2021/2178/oj

EU 2022/1214 – Commission Delegated Regulation (EU) 2022/1214 of 9 March 2022 amending Delegated Regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities URL: https://eur-lex.europa.eu/eli/reg_del/2022/1214/oj/eng

EU 2023/2485 – Commission Delegated Regulation (EU) 2023/2485 of 27 June 2023 amending Delegated Regulation (EU) 2021/2139 establishing additional technical screening criteria for determining the conditions under which certain economic activities qualify as contributing substantially to climate change mitigation or climate change adaptation and for determining whether those activities cause no significant harm to any of the other environmental objectives URL: https://eur-lex.europa.eu/eli/reg_del/2023/2485/oj/eng

EU 2023/2486 – Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to the sustainable use and protection of water and marine resources, to the transition to a circular economy, to pollution prevention and control, or to the protection and restoration of biodiversity and ecosystems and for determining whether that economic activity causes no significant harm to any of the other environmental objectives and amending Commission Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities URL: https://eur-lex.europa.eu/eli/reg_del/2023/2486/oj/eng

EU 2023/2631 – Regulation (EU) 2023/2631 of the European Parliament and of the Council of 22 November 2023 on European Green Bonds and optional disclosures for bonds marketed as environmentally sustainable and for sustainability-linked bonds. URL: http://data.europa.eu/eli/reg/2023/2631/oj

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Logistic process improvement in automotive industry using quality tools

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Abstract

The automotive industry continues to face numerous challenges that demand ongoing process improvement and system optimization. Incidents reported in the media have highlighted the relevant impact regarding companies' sustainability and brand image and consequently, the urgent need for stronger traceability mechanisms and faster response capabilities throughout the supply chain. This paper focuses on enhancing a key logistic process within automotive companies – the incoming material inspection – by applying the DMAIC (Define, Measure, Analyse, Improve, Control) methodology. This process is critical, as it directly influences production flow, product quality, and overall supply chain efficiency.

The DMAIC approach was selected due to its proven effectiveness in driving systematic process improvements, reducing defects, and establishing measurable control standards across manufacturing and logistics operations. Each phase of the methodology provides a structured framework with clearly defined objectives, control mechanisms, and deadlines to ensure consistent progress and accountability. Implementation of the DMAIC methodology resulted in a more transparent, standardized, and efficient inspection process. Quantitative and qualitative outcomes demonstrated significant improvements in process control and traceability. Furthermore, the initial project objectives were fully achieved and, in several instances, surpassed – validating the robustness of the applied methodology.

This analysis highlights the critical role of structured quality improvement frameworks, such as DMAIC, in managing increasingly complex logistics operations. In an industry shaped by digital transformation and sustainability imperatives, adopting data-driven methodologies fosters agility, consistency, and a culture of continuous improvement is essential. Beyond enhancing operational efficiency, such approaches strengthen collaboration, accountability, and long-term competitiveness within the automotive sector.

Keywords
process improvement, automotive industry, DMAIC methodology, incoming material inspection

1. Introduction

As the logistics department is a vital component of the production supply chain and for international trade relations (Gade et al., 2020), its continuous development and optimization must be regarded as a top priority by the company's management. Notable historical cases, such as Toyota's 2009 vehicle recalls affecting over 9 million units and Airbus's delays in A380 market entry due to weaknesses in its Product Lifecycle Management system (Norazlin et al., 2017), illustrate the significant operational and financial consequences of inefficiencies in quality control and supply chain processes. These examples underscore the urgency of implementing robust systems to reduce defects and improve responsiveness. Also, Lean practices (for instance these could be 5S (Sort, Set in order, Shine, Standardize, Sustain); Kaizen (Continuous Improvement); Value

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Stream Mapping (VSM); Just-In-Time (JIT) production; Kanban; Poka-Yoke (Error Proofing); Heijunka (Production Leveling); Total Productive Maintenance (TPM); Root Cause Analysis) were introduced into Toyota's system for creating value using minimum of resources (Albăstroiu Năstase et al., 2024).

In the automotive sector, where production is highly sensitive to delays, even minor interruptions can cause substantial losses. The trend from the last years needs the requirements for rethinking the process performance system (Dörnhöfer et al. 2016). MTTR, i.e. mean time to respond, can be a valuable key performance indicator (KPI) for incoming material inspection process in automotive industry for assessing and optimizing the Incoming Material Inspection process. Typical target ranges are between 2 and 8 hours for critical issues and 8–24 hours for major defects (Aiswarya S., 2024). Improving MTTR can be achieved through measures such as automated incident detection, employee training, standardized procedures, and predictive digital tools. This is demonstrated by Renault Group, which reduced response times and saved nearly €700 million through digital innovations (Renault Group, 2024).

Improving internal logistics in the automotive industry is crucial for reducing waste and increasing efficiency. The case study by Kocjan and Podloch (2025) highlights that unoptimized material flows and the absence of visual markings lead to unnecessary movements and time losses. The authors recommend implementing Lean tools such as 5S, visual management, and standardized procedures to create an organized and predictable environment that supports operational performance.

To systematically address process deficiencies, this study employs DMAIC methodology (Define, Measure, Analyze, Improve, Control), a structured quality improvement framework widely recognized for reducing defects and optimizing industrial processes (Subagyo et al., 2020). The application of DMAIC provides a clear structure for the entire project, enabling the selection of appropriate improvement solutions supported by the most effective Lean tools – advantages not typically offered by other frameworks (Rifqi et al., 2021). Also, the case study by Ramos et al. (2025) was conducted at a multinational automotive company, where they applied Lean tools – 5S, visual management, pull systems, and standardized work – to streamline assembly line material delivery. As a result, the company achieved significant improvements: over €108,000 in annual cost savings, reduced supply cycle time, optimized stock and ramp usage, and improved ergonomics by minimizing material handling and personnel requirements.

The DMAIC approach enables data-driven analysis of incoming material inspections, identification of root causes using tools such as Ishikawa diagrams and the 5Why method, implementation of targeted improvements, and continuous monitoring of key indicators including average response time, 24-hour deadline compliance, and frequency of recurring non-conformities.

This paper focuses on proposing an improved process for logistics departments in the automotive industry, with a particular emphasis on optimizing the Incoming Material Inspection process. By applying DMAIC to the Incoming Material Inspection process, this research aims to improve documented processes for operational efficiency, enhance supplier management, and ensure timely corrective actions, ultimately supporting continuous and efficient automotive production. The DMAIC framework can significantly reduce defects, minimize process variation, and optimize supply chain performance through mapping workflows, identifying root causes and statistical tools (Kurte et al., 2025).The study draws upon previous research as well as real-world industry challenges to highlight the critical need for enhanced traceability and faster response times. A key operational metric in this context is Mean Time to Respond (MTTR), which measures the time from the detection of a noncompliance to the initiation of corrective action.

2. Data and methods

This study focuses on evaluating the advantages of applying the DMAIC methodology to the selected process, emphasizing both the direct process improvements and the broader organizational benefits. While other continuous improvement methodologies, such as the PDCA (Plan-Do-Check-Act) cycle, are also highly valuable for enhancing the internal logistics environment (Amaral et al., 2022), the DMAIC approach was chosen for this study due to its comprehensive and data-driven framework. By systematically progressing through the five stages – Define, Measure, Analyze, Improve, and Control –, the project established a structured methodology for optimizing the Incoming Material Inspection process.

The first step of DMAIC methodology is defining the problem. Thus, the problem identified in this paper is the very large number of complaints received from the Incoming Material Inspection process during fiscal year 2023. Accordingly, the problem statement is formulated as follows: to achieve, within the Incoming Material Inspection process of an organization (for example Renault Group) a reduction in the average response time to the identification of non-compliant materials from 48 hours to 24 hours during fiscal year 2024.

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The second step of the methodology is to measure the data collected about the problem. In this stage, key activities include selecting key performance indicators (KPIs) aligned with the project objectives, collecting relevant data, applying appropriate measurement methods, using statistical analysis and data synthesis tools, and establishing a baseline that reflects the current process performance (Sushmith, 2024). KPIs are essential for monitoring and evaluating progress toward achieving the project objectives. For this project, aimed at improving the process of receiving materials from suppliers, three primary indicators were selected to provide a clear and objective measurement of performance:

1. Average response time to identify non-compliant materials – it measures the efficiency of the non-compliant materials management process.

2. Compliance with target response time – it reflects the organization's ability to meet rapid-response objectives.

3. Frequency of recurring non-conformities – it indicates the effectiveness of corrective actions and improvements in collaboration with suppliers.

For each KPI, specific calculation formulas and end-of-year targets for 2024 were defined to ensure measurable and verifiable success (1), (2), (3). These indicators collectively provide a comprehensive view of process efficiency, responsiveness, and quality improvement, enabling data-driven decision-making throughout the project.

$$\text{Average response time to identify non-conforming materials [h]} = \frac{\text{Sum of response times of all non-conformities}}{\text{Total number of cases}} \quad (1)$$

$$\text{Percentage of cases resolved within 24h [\%]} = \frac{\text{Number of cases resolved} < 24\text{h}}{\text{Total number of cases}} \times 100 \quad (2)$$

$$\text{Percentage of recurring non-conformities [\%]} = \frac{\text{Final number of recurring non-conformities}}{\text{Initial number of recurring non-conformities}} \times 100 \quad (3)$$

For each of the indicators mentioned above, a specific target was established for the end of 2024 to measure the success of the improvement project. The targets are as follows:

- Average response time to identify non-compliant materials – target of 24 hours.
- Compliance with target response time – at least 90% of cases resolved within 24 hours.
- Frequency of recurring non-conformities – 30% reduction in the number of recurring non-conforming materials.

These targets provide measurable benchmarks to evaluate the effectiveness of the implemented improvements and ensure that the project delivers tangible performance gains. Research was conducted using publicly available sources from several automotive companies. Among these, the local company Renault Group served as a key reference. Information was collected from the official website of Renault (n. d.), as well as from other reliable industry platforms.

Further, the collection of data relevant to the problem was carried out by systematically measuring the current response times to the identification of non-compliant materials (indicator 1), recording the number of cases resolved in less than 24 hours (indicator 2) and the number of recurring non-compliances (indicator 3) during fiscal year 2024.

A qualitative analysis of the data was conducted to categorize the types of complaints received in the Production Process, allowing for a synthesis of the information collected over the previous year. In addition, a quantitative analysis was performed to determine the frequency of each complaint type during 2024, as presented in Table 1.

For a statistical analysis, the data from Table 1 were organized into a Pareto diagram, shown in Figure 1, enabling the application of the Pareto principle. This analysis revealed that a small number of complaint types (approximately 20%) accounted for the majority of occurrences (around 80%). By using the Pareto diagram, it was possible to identify the complaint types that exceeded the 80% threshold and thus represent the critical issues requiring priority attention.

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Table 1. Qualitative and quantitative sorting of complaints registered in 2023

	January	February	March	April	May	June	July	August	September	October	November	December	TOTAL
Non-retrievable items	13	19	32	13	20	16	11	12	10	25	20	30	**221**
Retrievable items	9	13	7	18	10	11	9	8	15	11	12	9	**132**
Labeling issues	3	0	3	5	8	9	0	1	3	6	5	7	**50**
Color/appearance not in compliance	5	6	8	5	9	12	11	8	7	9	10	15	**105**
Out of stock/shortage	8	7	9	5	3	7	6	4	5	8	6	6	**74**
Material quality issues	9	10	15	14	8	9	12	11	10	8	9	20	**135**
Contamination or dirt	9	6	8	7	10	9	2	5	9	8	6	4	**83**
TOTAL	**56**	**61**	**82**	**67**	**68**	**73**	**51**	**49**	**59**	**75**	**68**	**91**	**56**

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Applying the Pareto principle (where 20% of causes generate 80% of defects) allowed the identification of the most significant problem: the high number of non-conforming parts received from suppliers (Fig. 1). By focusing on this issue, the greatest overall improvement in the process could be achieved. Not all types of complaints were addressed due to budgetary and resource constraints, making it necessary to prioritize interventions. Consequently, the most effective solution was selected – reducing the volume of non-conforming parts –, which directly impacts the efficiency and reliability of the production process.

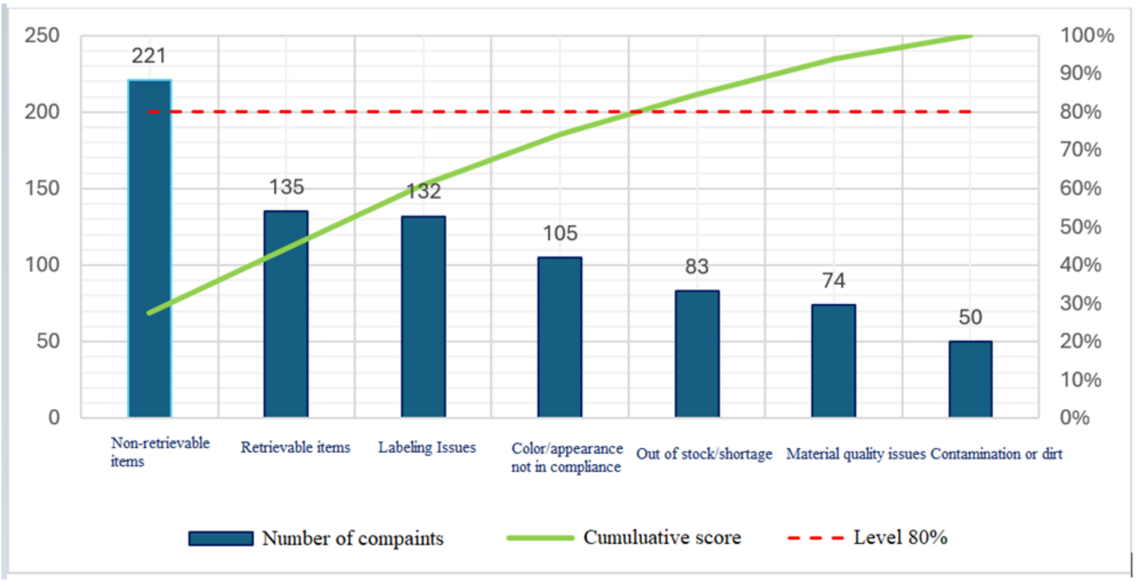

Figure 1. Pareto diagram: complaints registered in the production process during 2024

The final stage involved establishing a reference baseline to reflect the current performance level. This was represented through three graphs, each illustrating the current state of the selected performance indicators alongside the proposed targets for the following year, as shown in Figures 2, 3 and 4. These visualizations provide a clear comparison between the existing performance and the desired outcomes, serving as a benchmark for monitoring progress and guiding improvement efforts.

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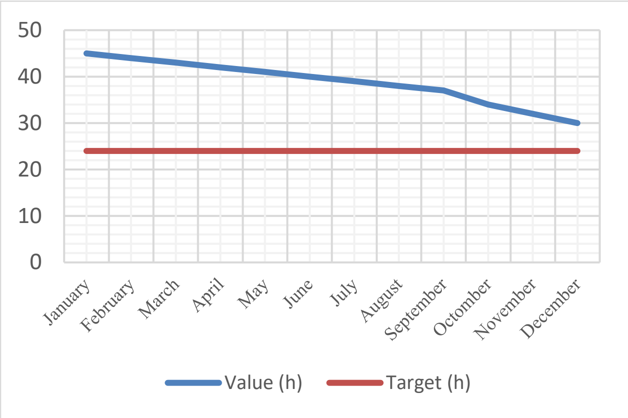

Figure 2. The current response times to the identification of non-compliant materials in years 2020–2023

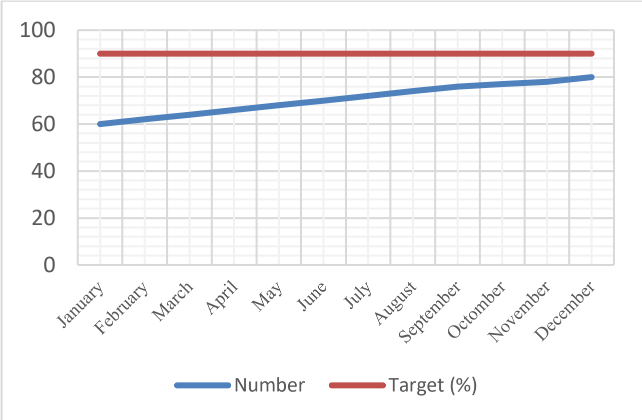

Figure 3. The number of cases resolved in less than 24 hours in years 2020–2023

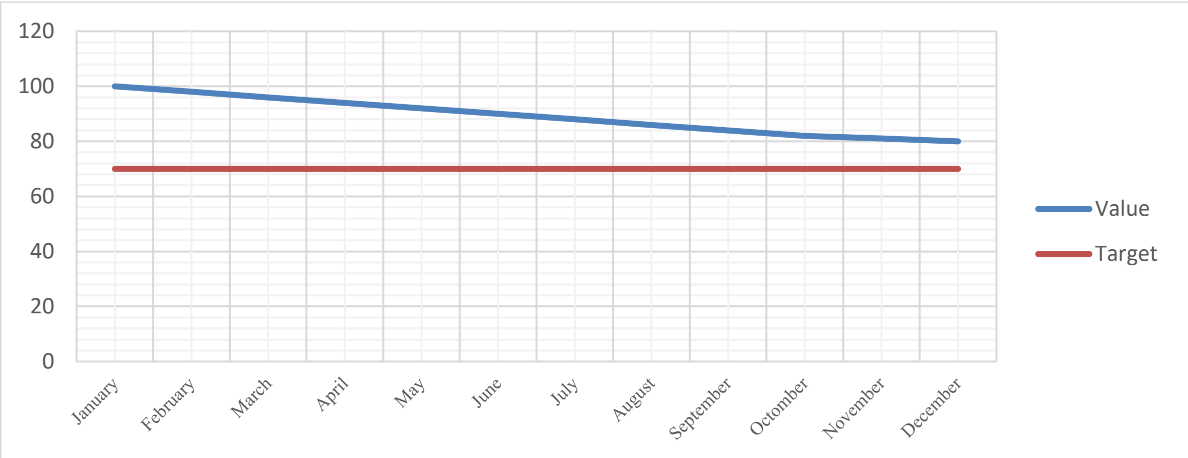

Figure 4. The number of recurring non-compliances in year 2024

The third stage of DMAIC is analyzing the data collected. In the third stage, the focus is, therefore, on identifying the root causes of the problem under investigation. In this stage, a lot of authors used a range of quality tools such as cause-and-effect diagrams, Pareto analysis, statistical process control charts, and failure mode and effects analysis (FMEA) to ensure rigorous problem identification and solution development (Che, 2016). Key activities in this stage include examining potential causes using tools such as the Ishikawa diagram and subsequently determining the root causes with methods like the 5Why approach (Sushmith, 2024). Root cause analysis and structured problem-solving tools are essential for continuous improvement in automotive logistics and the use of quality tools such as Ishikawa diagrams, DMAIC methodology, and the 5Why technique is very useful to identify and eliminate sources of inefficiency. By applying these methods, the study achieved significant waste reduction and improved delivery times, demonstrating how systematic analysis and corrective actions can enhance internal logistics performance (Amaral et al., 2022).

Building on the Pareto analysis from the previous stage, the most critical complaint was identified as “Large number of defects/non-retrievable items”, which, if addressed, would produce the greatest overall improvement. To investigate the underlying causes of this issue, one of the best known models, the Ishikawa diagram (Figure 5), was employed (Luca, 2016). This tool allowed the team to systematically explore potential causes across four main categories:

1. Causes related to personnel,
2. Causes related to equipment,
3. Causes related to methods, and
4. Causes related to the working environment.

This structured approach considered the possible contributing factors and facilitate the identification of the root causes to guide targeted improvement actions.

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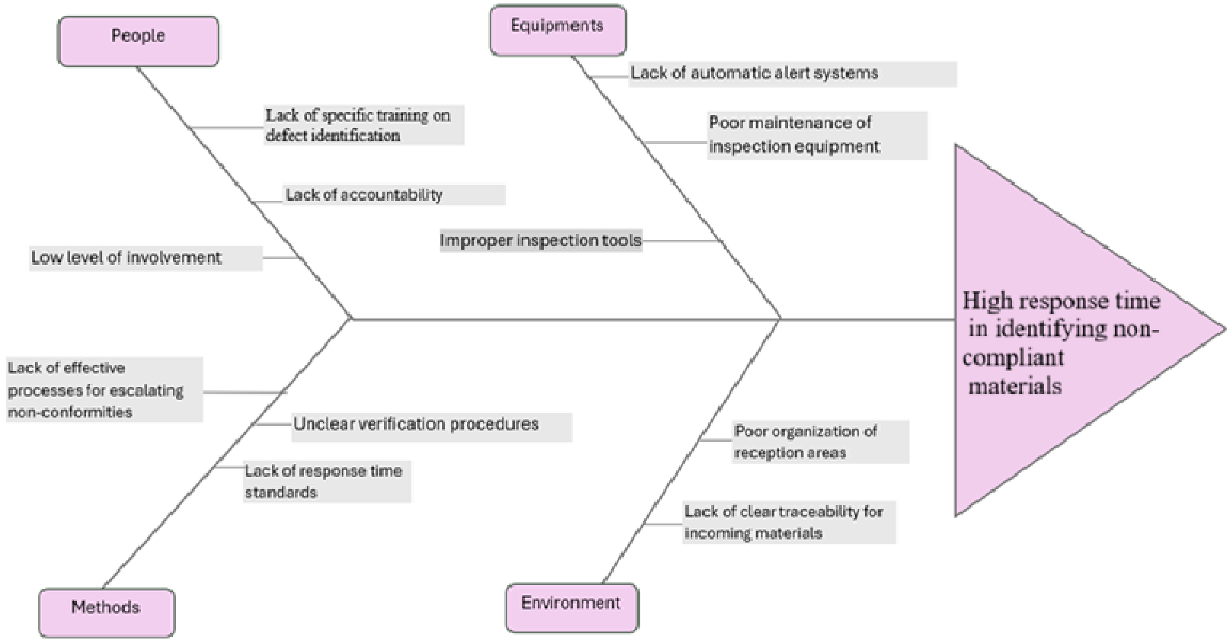

Figure 5. Ishikawa diagram for identifying possible causes of the determined problem

The Ishikawa diagram provided a structured visualization of the potential root causes, allowing them to be classified into four main categories:

- **Manpower – Human-related causes:** lack of specific training in defect identification, low employee engagement, and insufficient accountability within the inspection team.
- **Machine – Equipment-related causes:** use of inadequate inspection tools, absence of automatic alert systems, and poor maintenance of verification equipment.
- **Mother nature – Environmental causes:** inefficient organization of receiving areas and lack of clear traceability for incoming materials.
- **Method-related causes:** unclear inspection procedures, absence of standardized response times, and lack of effective escalation processes for nonconformities.

The decision to focus on only four M categories, rather than the traditional six, was based on the company's specific context. While theoretically including all six Ms could provide a more comprehensive view of factors affecting the process, in practice some aspects – such as management processes or measurement methods – were either too costly or difficult to modify relative to the expected benefits. Implementing major changes in these areas would have exceeded budget constraints and risked company resources. Therefore, the analysis was intentionally simplified to four Ms to focus on the factors with the greatest practical impact. This approach allowed the project team to direct efforts toward solutions that were both feasible and effective, ensuring meaningful improvements in the Incoming Material Inspection process without compromising financial or operational sustainability.

The potential causes identified through the Ishikawa diagram were further analysed using the 5Why method, which helps determine not only possible causes but also the true root causes of a problem, enabling the selection of solutions that address the core issue. All identified potential causes were incorporated into the 5Why analysis, as shown in Figure 6.

During this analysis, most of the causes from the Ishikawa diagram were examined. Exceptions either appeared indirectly through the decomposition of other causes or had no further underlying causes, making additional analysis unnecessary. The 5Why analysis revealed several root causes; however, the most frequently occurring and therefore the primary root cause was identified as the **lack of a standardized and efficient process for identifying and managing non-compliant materials**. This insight provides a clear focus for targeted improvement actions that will have the greatest impact on resolving the problem.

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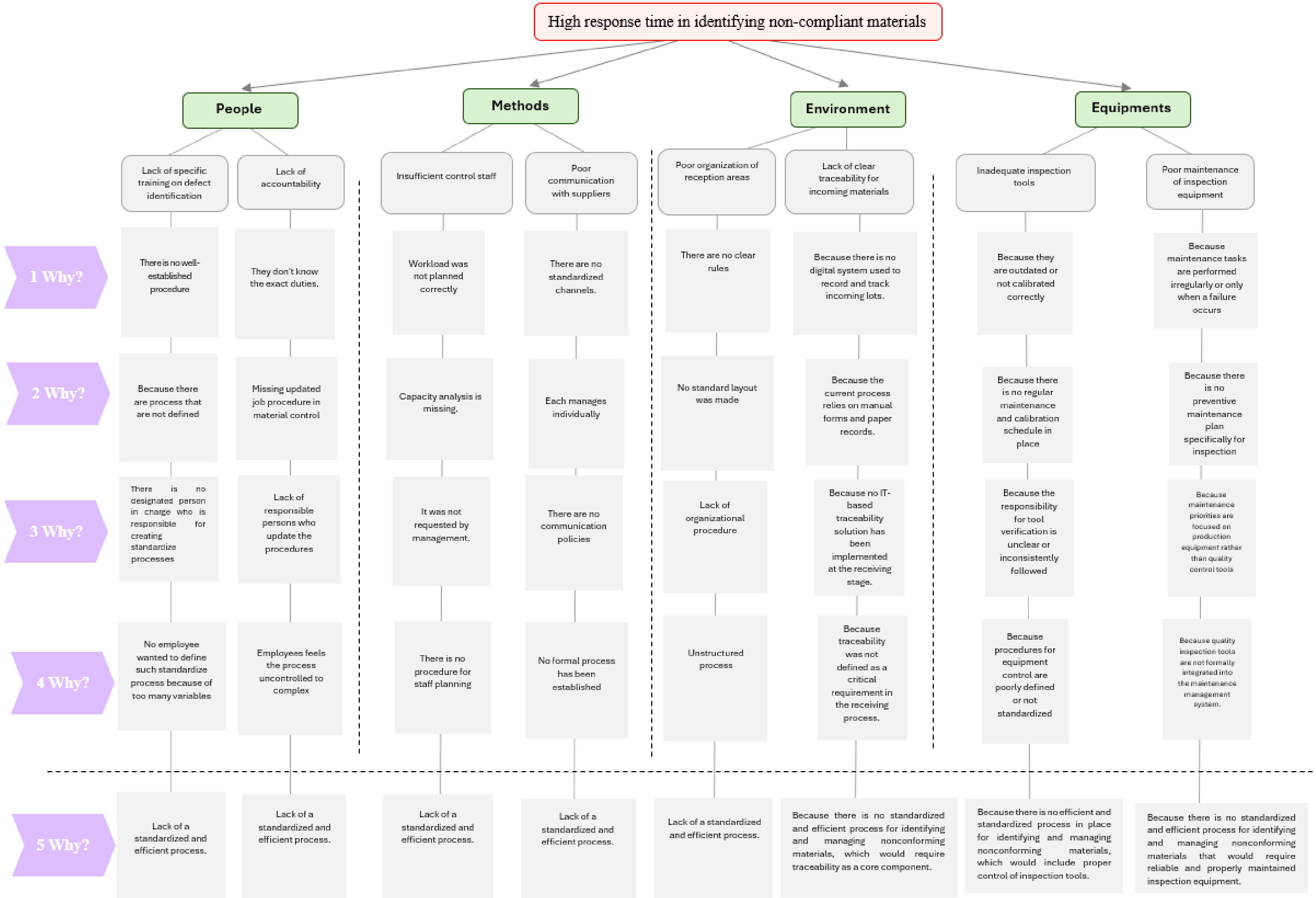

Figure 6. The 5Why's analysis

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Proceeding to the next stage of the methodology, finding the best improvement solution(s), the focus was on developing and implementing solutions that directly address the root causes identified in the previous phase (Sushmith, 2024). Ideas were generated using brainstorming sessions and by reviewing similar situations within the company, following established practices in large organizations. Insights were also drawn from Good Practice Reports and Lessons Learned Reports from industry leaders such as Toyota and Mercedes.

To ensure a comprehensive analysis, a centralized table (Table 2) was created. This table links each identified root cause to the corresponding proposed solution, assigns responsibility for implementation, and specifies the estimated implementation timeline. This structured approach facilitates accountability, ensures clarity of action, and allows for efficient monitoring of progress throughout the improvement project.

Table 2. Solutions identified for the root causes of the problem

ROOT CAUSE	PROPOSED SOLUTION	RESPONSABILE PERSON	DEADLINE
Lack of a standardized and efficient process	Develop and implement a standardized workflow for incoming material inspection, including clear guidelines, roles, and KPIs to ensure process consistency and efficiency.	Quality Manager	150 days
Because there is no standardized and efficient process for identifying and managing noncomplying materials, which would require traceability as a core component	Establish a traceability system integrated with a standardized nonconformity management process, enabling real-time tracking, escalation, and resolution of issues with incoming materials.	Quality Manager and IT Department	170 days

As shown in Table 2, most of the proposed solutions focused on improving the Incoming Material Inspection process or creating a more efficient version of it in various forms. Accordingly, the key improvement proposed for the primary problem – "Lack of a standardized and efficient process" – was the development of a fully documented process, as outlined in Table 2. The current process for 2024 is presented in Figure 10, while the improved process proposed in this study is detailed in Figure 11 below.

Following implementation, the project included ongoing monitoring to evaluate the effects of the solution. Throughout 2024, complaints from production regarding scraps and defective parts were recorded, alongside observations of changes in other types of complaints. This monitoring enabled the assessment of the impact of the new process on overall production quality and helped verify the effectiveness of the implemented improvements.

For the stage fifth of the DMAIC methodology, improving, the process improved are presented in Figure 10 and Figure 11 in the Results and discussion section.

The final stage of the DMAIC methodology, monitoring the changes made, focuses on tracking the implemented improvements, sustaining progress, and preventing regression to previous conditions. Key activities in this stage include monitoring the system and effectively communicating the changes to all relevant stakeholders (Sushmith, 2024). In line with this, the monitoring of complaints recorded throughout 2024 is summarized in Table 3, providing a clear view of the impact of the implemented improvements on the Incoming Material Inspection process and overall production quality. Additionally, key stakeholders, including the Quality Department Manager and Production Managers, were informed about the implementation of this improvement plan to ensure alignment and support for enhancing organizational performance.

Table 3. Qualitative and quantitative sorting of complaints registered in 2024

	January	February	March	April	May	June	July	August	September	October	November	December	**TOTAL**
Non-retrievable items	3	9	12	13	12	16	10	6	5	5	10	10	**85**
Retrievable items	3	0	3	5	8	9	0	1	3	6	5	7	**50**
Labeling Issues	3	0	3	5	8	9	0	2	5	10	9	7	**59**
Color/appearance not in compliance	5	6	8	5	9	2	6	3	7	4	5	5	**65**
Out of stock/shortage	8	7	9	5	3	7	6	4	5	8	6	6	**74**
Material quality issues	5	6	8	5	9	2	6	3	7	4	5	5	**65**
Contamination or dirt	9	6	8	7	10	9	2	5	9	8	6	4	**83**
TOTAL	**36**	**34**	**51**	**45**	**59**	**54**	**30**	**24**	**41**	**45**	**46**	**44**	

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3. Results and discussion

The results of this study are reflected in the performance status of the defined indicators, which were continuously monitored throughout 2024. These measurements demonstrate the sustained progress achieved following the implementation of the improvement project. In addition, the newly developed and optimized process itself represents a significant outcome of this research, providing a more efficient and standardized approach to incoming material inspection. The evolution of the key performance indicators is illustrated in the figures below (Figures 7, 8 and 9), highlighting the positive impact and consistency of the improvements over time.

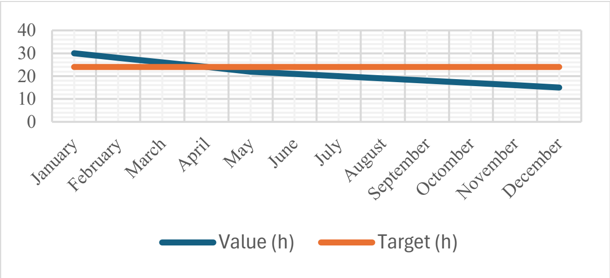

Figure 7. The current response times to the identification of non-compliant materials

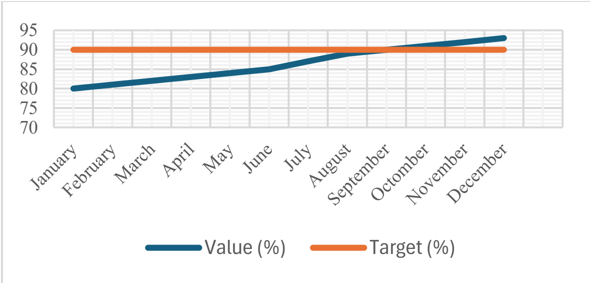

Figure 8. The number of cases resolved in less than 24 hours

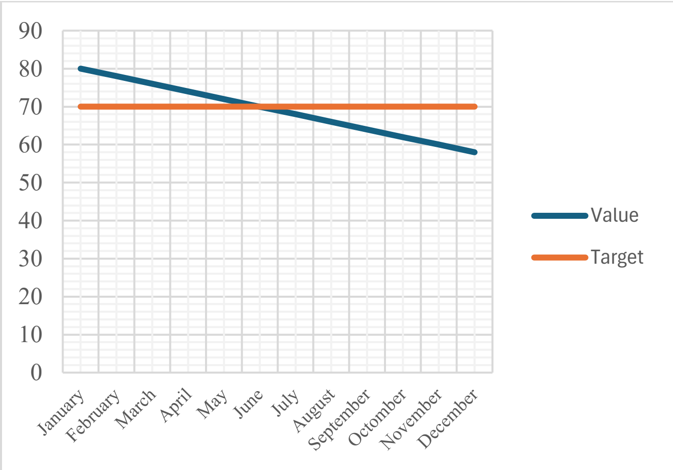

Figure 9. The number of recurring non-compliances in 2024

Figure 7 illustrates a consistent monthly reduction in the measured time (hours), decreasing from 30 hours in January to 15 hours in December. This downward trend represents a substantial improvement compared to the established target of 24 hours. Although the target was slightly exceeded during the first three months, from April onward all recorded values remained at or below the desired threshold. This consistent performance demonstrates the effectiveness and sustainability of the implemented improvement measures, confirming that the actions taken successfully reduced processing time and stabilized the process throughout the year.

Figure 8 shows a steady month-over-month increase in performance, improving from 80% in January to 93% in December. Although the target value of 90% was not reached during the first eight months, it was achieved in September and subsequently exceeded in the following months. This upward trend demonstrates the positive impact of the implemented improvement actions, reflecting a consistent and sustained enhancement in process performance over the year. The results confirm that the corrective measures applied were effective in driving progress and maintaining performance above the established target.

Figure 9 illustrates a continuous decline in monthly values, decreasing from 80 in January to 58 in December, while the target remained constant at 70. The target was first met in June; however, from July onward, the results consistently fell below the target and continued to decline through the end of the year. This downward trend suggests the emergence or escalation of performance issues, resource limitations, or process inefficiencies. To address these deviations, further analysis is recommended to identify root causes and implement corrective actions aimed at restoring and stabilizing performance at the desired level.

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As shown in Table 2, most of the identified solutions focused on improving the Incoming Material Inspection process or developing a new, more efficient version of it in various forms. Accordingly, the proposed improvement for the problem addressed is the creation of a documented and standardized process, aligned with the program outlined in Table 2, specifically in the section addressing the *"Lack of a standardized and efficient process."* The current process, reflecting the state of operations in 2024, is presented in Figure 10, while the proposed improved process developed in this study is detailed in Figure 11.

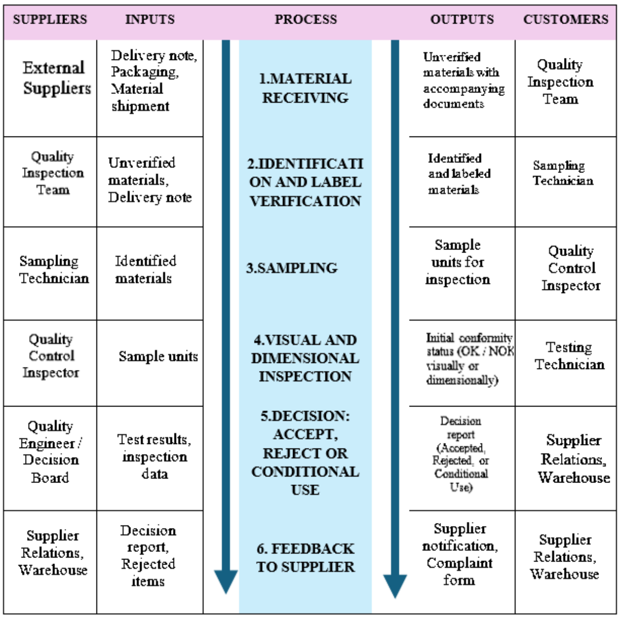

Figure 10. The current process for the year 2023

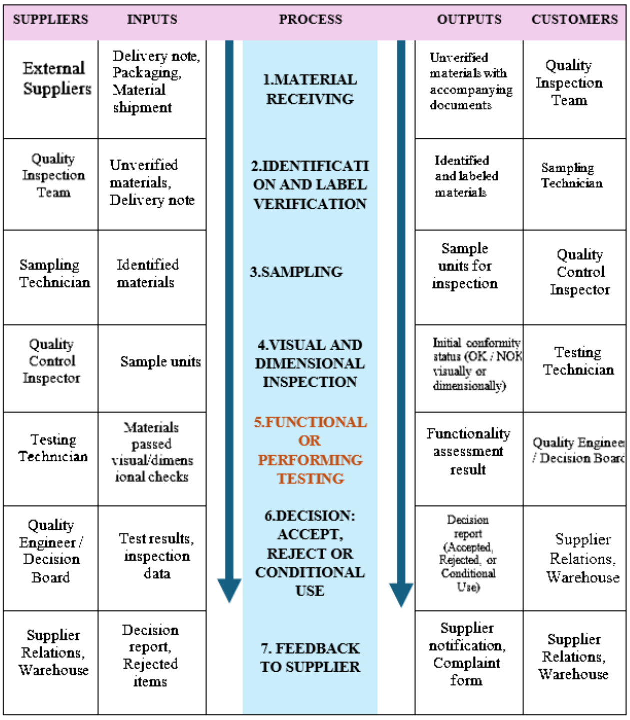

Figure 11. The improved process for the year 2024

The implementation of the improvement project generated significant results in the performance of the Incoming Material Inspection process within the automotive industry. Through the structured application of the DMAIC methodology, measurable progress was achieved and closely monitored at each stage. The initial analysis of performance indicators identified inefficiencies related to inspection time, defects detection accuracy, and the consistency of supplier evaluation criteria. After defining the root causes, targeted solutions were implemented, including the redesign of the Incoming Material Inspection process. As a result, the average inspection time per delivery decreased considerably, enabling faster material processing and improved workflow efficiency. The defects detection rate also increased, reflecting enhanced process control and quality assurance. Overall, the application of DMAIC led to a more transparent, standardized, and efficient inspection system. The objectives established at the start of the project were fully met and, in several cases, exceeded – demonstrating both the effectiveness of the implemented measures and the value of cross-functional collaboration. The improvements achieved confirm the strategic importance of continuous improvement initiatives at this stage of the supply chain and underscore their positive impact on organizational performance and competitiveness.

4. Conclusion

This study demonstrated the effectiveness of applying the DMAIC methodology to optimize the Incoming Material Inspection process in the automotive industry. By systematically addressing root causes and implementing targeted improvements, the project achieved measurable and significant results: the average response time to identify non-compliant materials was reduced from 48 hours to 15 hours, surpassing the initial target of 24 hours; compliance with the 24-hour resolution target increased from 60% to 93%, and recurring non-conformities decreased by 27% compared to the baseline. These improvements not only accelerated corrective actions but also enhanced process transparency, supplier accountability, and overall production stability.

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The originality of this research lies in its integration of DMAIC with automotive logistics, providing empirical evidence that structured quality tools can deliver rapid, quantifiable gains in a highly complex supply chain environment. Unlike prior studies that focused primarily on assembly or production lines, this work addresses a critical upstream process – material inspection – where delays propagate through the entire value chain. By presenting a validated framework supported by concrete performance metrics, this paper contributes to applications in automotive logistics and offers a replicable model for similar contexts.

Strategically, the findings underscore that improving responsiveness and traceability in material inspection is not merely an operational enhancement but a competitive imperative. Faster response times and standardized workflows strengthen resilience against supply disruptions, reduce waste, and support sustainability objectives by minimizing resource losses. This approach can be generalized across other automotive processes and extended to adjacent industries, positioning organizations to meet the dual challenge of operational excellence and environmental responsibility. In an era where agility and sustainability define market leadership, structured methodologies like DMAIC represent a cornerstone for long-term competitiveness in the automotive sector.

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