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Sustainability Integration in Railway Manufacturing Engineering Projects: A Conceptual Review

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Abstract: *Sustainability has become a critical aspect of railway manufacturing engineering projects due to environmental concerns, regulatory requirements, and the need for long-term economic viability of large-scale infrastructure systems. Beyond strict regulations, innovative technologies, and stakeholder coordination, Germany is one of the examples of the progressive implementation of sustainability principles in the railroad industry. The paper provides a concept synthesis of the sustainable practices in the railway engineering project based on the literature in manufacturing engineering, railway systems, project management and sustainability research. The concept of sustainability is encompassed in the project lifecycle, design, material selection, production processes, digitalization, supply chain management, and governance structures. Among the areas of focus, lifecycle orientation can be mentioned, along with the use of green technologies, the adoption of digital technologies, and tools that facilitate sustainable decision-making, e.g., BIM, automation, and data-based systems. The articles highlight the significance of stakeholder engagement, alignment of regulations, and the sustainability of the supply chain to project success. There are also persistent challenges that are addressed, high initial costs, technical integration issues, organizational resistance and regulatory discrepancies. Experiences in Germany provide insight into how sustainability can be improved through regulatory compliance, digitalization, and collaboration. The research offers systematic insights for future research and practice that could be used to enhance environmental performance, functional effectiveness, and sustainability.*

Keywords: *Sustainable Practice, Sustainability, Railway Manufacturing, Germany, Life-Cycle Assessment.*

I. INTRODUCTION

The principles of sustainability have become relevant in the engineering profession and industrial development both in the United States and globally with the implementation of the United Nations Sustainable Development Goals (UNSDGs) in 2015. There is increased pressure on companies to minimize their effects on the environment by the government and other stakeholders, but without impacting their productivity. This pressure is increasing based on the escalating interest in the environmental degradation, resource depletion and climate change among peoples and this has made the demands on responsible industrial and engineering practices even more demanding [1].

Sustainability in engineering is understood as the resilience of the system over time, its cycles, long-term planning, and its orientation in accordance with national and international environmental objectives instead of compliance and resource use. Sustainable engineering comprises of integrating “Renewable Energy (RE), minimizing residues and emissions, recyclable or low-impact material use, and lifecycle cost analysis [2].

The railway industry is a strategically significant pillar of sustainable mobility and decarbonized agenda in Germany, where the railway manufacturing engineering project takes the core of the national and regional sustainability agenda. There is an increasing emphasis on sustainable railway development and the manufacturing engineering phase has not been left behind in this move. Decisions at this stage include critical design, material, production method and supply chain management. With sustainable practices at this level, the railway manufacturers will not only be capable of enhancing the efficiency of operations, but can also reduce the lifecycle expenses and stay in line with the requirements of the evolving environmental legislation. Moreover, manufacturing that is sustainable is one of the supports of national and regional climate policies, particularly in the case of developed railway markets such as Europe and Germany, where the rail transport constitutes a significant target of the decarbonization policy and one of the central spheres of the market [3].

Despite increased scholarly research on sustainability in railway systems, the literature remains disjointed across lifecycle assessment, green technologies, digitalization, supply chain management, and stakeholder governance. Research such as that currently available tends to treat these dimensions individually, with little integrative attention to the manufacturing engineering phase in the German railway environment.

Filling this gap, the given review paper summarizes the available literature on the topic of sustainable manufacturing engineering in railway projects in Germany. It explores the major concepts of sustainability, the nature of the project, and practices of lifecycle orientation, green technologies and digitalization, the supply chain and stakeholder focus, and the problem of implementation and offers an elaborated and situation-specific viewpoint to inform academic studies and practice in the industry.

II. CONCEPT OF SUSTAINABILITY IN MANUFACTURING ENGINEERING

The engineer is at the forefront of developing infrastructure, technologies, and systems that not only meet immediate functional needs but also reduce environmental waste and contribute to long-term efficiency [4]. In economies where technology is highly developed like Germany, engineers are given a crucial role to bring the manufacturing innovation in line with national sustainability goal especially in those sectors where the environmental regulation and high technology standards are highly established [5]. By linking project goals with wider environmental, economic, and social factors, “Sustainable Practices” (SP) form the fundamental basis of responsible engineering and industrial development [6].

A. Definition and Scope of Sustainable Practices in Manufacturing

"Sustainable Practices" (SP) refers to collection of methods, concepts, and strategies that aim to meet current requirements at the expense of future generations [7]. In order to save the environment, conserve natural resources, and maintain the long-term sustainability of the economy and even civilization, these methods are thus applied in engineering and industrial processes. In the German manufacturing context, SP are increasingly shaped by national climate targets, circular economy policies, and compliance with European Union environmental directives.

Using eco-friendly materials, reducing waste and emissions, adopting energy-efficient technology, and developing with the overall "life cycle of a product" (LCP) in mind are all ways that manufacturing engineering sustainability operates [8].

Since ethical labor, stakeholder participation, rules, and standards are all included in this vocabulary, the scope of the SP is broader than that of the environmental term. In business contexts, SP can be helpful in making sure that the current systems are reliable, efficient, and in line with the UNSDA's global sustainability goal, especially when performing a “Manufacturing Engineering Project” (MEP).

B. Integration of Sustainable Practices in Manufacturing Engineering Projects

In MEP, adopting SP is considered a vital factor which contributes to the increase of system robustness, reliability, and flexibility. For German manufacturing organizations, integrating sustainability at the project planning and execution stages enables alignment between organizational performance objectives and national as well as international sustainability frameworks, one of which is the “United Nations Sustainable Development Agenda” (UNSDA) [9]. The two-way process guarantees that the projects in manufacturing engineering will benefit not only the organizations in terms of performance but also society and the environment as a whole.

Furthermore, utilization of SP in manufacturing engineering promotes development of new ideas by urging the application of cutting-edge production methods, digital instruments, and process automation that are all directed towards improving energy efficiency and waste reduction. In addition, eco-friendly manufacturing setups enhance the practice of continuous improvement and the gaining of long-term competitive advantage by fostering strong and reliable supply chains and using eco-friendly procurement methods. Therefore, the manufacturing engineering sector's sustainability has changed over time from being a requirement driven by compliance to a strategic priority that has a direct impact on project success, organizational image, and the long-term growth of industry.

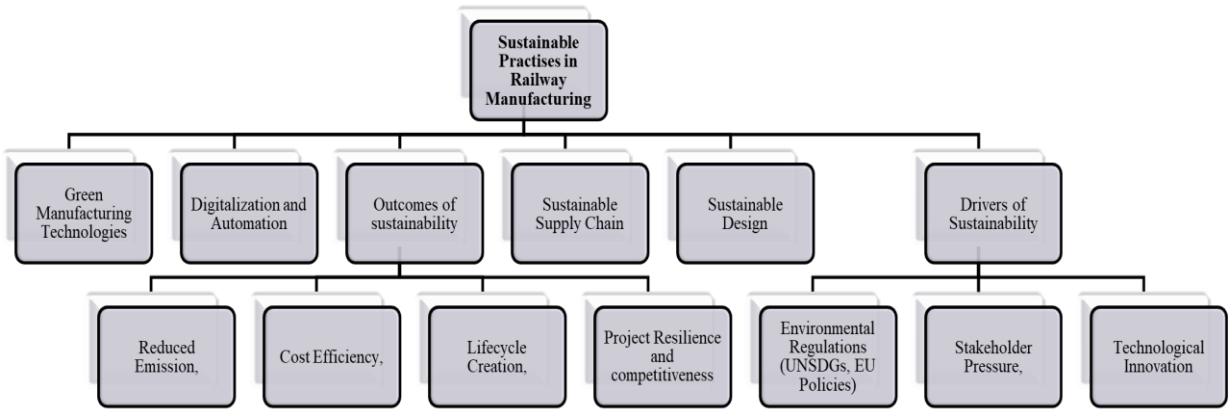

Figure 1 : Sustainable Practice in Railway Manufacturing Engineering Project.

To integrate the various sustainability dimensions discussed above, a conceptual framework is presented in Fig. 1, illustrating the integration of SP within railway MEPs. This framework depicts the incorporation of SP into railway MEP, highlighting the participation of regulatory drivers, technological enablers, and sustainability outcomes. Railway Manufacturing Engineering Projects: Context and Characteristics

With the complexity and scale of railway engineering projects, it is more essential than ever to ensure that sustainability is at least part of the factory's operations and that this influences the project's overall success [10]. Economic sustainability in railway engineering projects includes cost reduction, strategic project appraisal, and effective resource use to optimize financial gains.

The industry is expanding to use more green technologies, such as energy-saving rolling stock which will help to maximise performance and minimise its environmental impact, in response to the growing population's demand for better transportation and government efforts to reduce emissions and meet climate goals. Additionally, the railway industry's engineering and manufacturing, which include the creation of automobiles and their parts, as well as the upkeep of infrastructure, is a rich area for sustainable practices [11]. Germany's railway sector, as a central component of its national decarbonization and sustainable mobility agenda, has emerged as a key arena for the application of such green manufacturing technologies [12].

SP could be essential in business contexts particularly when carrying out MEPs to ensure that the existing systems are dependable, effective, and in line with the goals of UNSDA in ensuring global sustainability [9].

Additionally, in the production of the railways, engineering projects are usually characterized by complicated supply-chain and a number of parties, such as the governmental bodies, vendors, and consumers. Sustainability applications in the project management process does not only aid in the communication and transparency but contributes to responsible sourcing, ethical procurement, long-lasting supplier relations throughout the networks. Detailed plans do not only enhance the management of the projects but also increase the tolerance of the projects to the uncertainty surrounding the economy, regulations, and technology.

III. LIFECYCLE - ORIENTED SUSTAINABLE MANUFACTURING PRACTICES

Life cycle assessment (LCA) is an essential practice which can be used by the railway sector to promote sustainability. LCA examines the entire environmental impacts of any project, whether it is the purchase of project materials or even the death of the project. This allows them to make choices in their favor towards their sustainability goals. With the introduction of LCA in the project planning, the engineers can advance processes and minimize their impact on the environment throughout the lifetime of the railway assets [10] Since the railway business now uses environmentally friendly procedures, the cooperation of the governments, researchers, and manufacturers is essential.

The process of creating the railway track is shown in Fig. 2 and the modules that are reported indicate the materials and components that should be considered in each module.

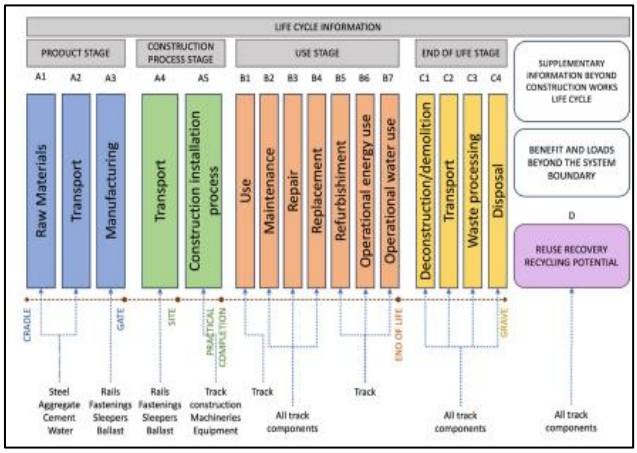

Figure 2 : Framework for Evaluating the Economic, Social, and Environmental Performance of Railway Track Systems [13]

LCA could be useful in identifying opportunities and risks associated with the sustainability of supply chain (SC). Lifecycle-based knowledge helps organizations to evaluate the supplier practices, material sourcing and downstream effects, thus empowering sustainable supply chain management in railway manufacturing projects. In the anthology of stakeholder management and competitive advantage, a framework is available in [14], which discusses the significance of strategic

decision-making and the relevance of stakeholder management [15]. In addition, also find out that green HRM practices can result in a successful shift in stakeholder pressure towards environmental performance that can serve to enhance stakeholder satisfaction as well as environmental performance [16]. Discuss the ways in which acting decisively can be used to solve urgent issues such as poverty and global warming.

IV. GREEN TECHNOLOGIES AND DIGITALIZATION IN RAILWAY MANUFACTURING

The green technologies and digitalization promote the sustainability in the railway manufacturing, meaning that the environmental goals are placed in the production, which allows gaining efficiency and reducing emissions, as well as ensuring the resilience of operations over time.

A. Adoption of Green Technologies

The use of green technology in railway engineering is growing in popularity as a strategy to reduce pollution's negative environmental impacts and increase overall energy efficiency. Some of the new technologies that have been implemented include the electrification of the rail network, the use of rolling stock which uses less energy, use of lighter material and installation of automation in the production plants. Such approaches aim to maximize resource utilization, reduce emissions, and improve lifecycle efficiency across railway manufacturing operations [17].

The waste management and recycling technology were also in the list of the green technologies which help the environment a lot by making it possible that the by-products of the manufacturing process or the died-off elements are re-used or disposed safely. One case is the rolling stock design that is modular and therefore allows easier refurbishment or recycling of the parts, thereby, minimizing the environmental impact of multiple project lifecycles. Such practices are economically viable and socially and politically acceptable, as they do not contradict the government policies and decarbonization processes, and Germany's transportation system, economy, and environmental policies all depend significantly on its railroads [3].

B. Digitalization and Process Automation

Railway operations are becoming increasingly digitized, rolling stock is increasingly energy efficient, and RE is being incorporated into railways. Additionally, Germany is spending money on research and development to help design trains that run on hydrogen and batteries, which will help the industry develop a sustainable mobility future [18]. These developments indicate a change in engineering and policy to guarantee that the railway sector serves as the backbone of climate-neutral transport in Germany and throughout Europe.

Automation also improves sustainability results as it allows manufacturing plants to meet high environmental norms and optimize production processes and waste of energy. Digitalization can be used when combined with green technologies to avoid stagnation, improve project management, and ensure their stability over time. When properly introduced by the railway manufacturers, these technologies are more likely to fulfill the environmental requirements, decrease the costs of running the business, and preserve a competitive advantage in the markets which are getting increasingly more environmentally friendly [16].

V. SUPPLY CHAIN AND STAKEHOLDER CONSIDERATIONS IN RAILWAY MANUFACTURING

Best management of the supply chain and the active involvement of the stakeholders play a key role in ensuring the sustainability of the railway manufacturing process, which ensures that the environmental, economic, and social goals are achieved and helps to maintain the stability of the operations and work of the organization in the long-term.

A. Sustainable Supply Chain Management

The literature has common knowledge on Sustainable Supply Chain Management Practices (SSCMPs) which are a determinant of environmental and operational performance in manufacturing sectors. Supply chain sustainability in the manufacturing industry of railways is a necessity like the production on-site. Manufacturers should make energy inputs, production components, and procurement of raw materials in a reasonable way. The green procurement, traceability of materials and supplier audits are some of the practices that have reduced the environmental footprint of the manufacturing process besides assisting in the compliance of international sustainability norms [15]. In Germany, European Union sustainability directives and national supply chain due diligence requirements are other practices strengthened.

The railway system could be more adaptive and resilient, with SSCMPs and digital technologies that will enhance efficiency and minimize waste of resources [19]. The likelihood of saving money and having a positive environmental impact is highly enhanced when a circular economy (CE) model is adopted that entails recycling and reusing of goods. It is therefore important to keep on with research and innovation of the practices and methods which are sustainable [20].

B. Stakeholder Engagement and Governance

Green technologies, such as energy efficient rolling stock, electrified lines and automated systems, are being more widely applied in the railway sector to achieve maximum performance and minimum impact on the environment in response to the increase in the public demand to make the environment better by transportation and government actions to cut down the emissions and meet the climate targets.

There are several issues which are the concern of the German government such as the modernisation and electrification of the railway industry, incurring massive government expenditure, the encouragement of the rail which is a less risky way to travel than roads, the continued emphasis on the mitigation of carbon impact and the adoption of transportation more in line with ecological friendliness [21].

The stakeholders comprising of the government agencies, suppliers, customers and the local communities are the major determinants of success or failure in the adoption of the sustainable practices. Effective stakeholder engagement not only reaffirms the sustainability strategies are not out of the fold, but also introduces new communication and solidifies the project control. The literature consistently emphasizes that robust governance and proactive stakeholder involvement improve decision-making quality and contribute to long-term project and sustainability performance [22].

VI. CHALLENGES AND BARRIERS TO IMPLEMENTING SUSTAINABLE PRACTICES

Despite the significant benefits, sustainable practices continue to fail to gain acceptance due to technical and operational difficulties. Among the greatest challenges that organizations have to deal with, the high expenses of green technologies, extended production times, and the issue of their compatibility with the already established systems can be mentioned [11].

Attempting to manage the energy consumption in a manner that would not result in the loss of the production efficiency, ensuring that the quality level would remain the same, and training workers to use new equipment are one of the primary issues of its functioning. Besides, the renovation of old production units to meet the recent sustainability requirements tends to be a costly engineering design and resource intensive task [17].

Among the organizational barriers for adopting sustainable practices are staff awareness, lack of training, and opposition to change [23]. The other obstacle is the variation of regulations in various regions, which makes manufacturing projects adhere to diverse environmental regulations in different jurisdictions.

After these barriers are established, they can be addressed through good leadership, encouraging policies and developing people. Among the most valuable activities are training, setting sustainability targets, and fostering a firm culture that values environmental responsibility. Conversely, strategic planning with the intention of implementing sustainability in the corporate, procurement, and decision-making processes will not only help to eradicate organizational and regulatory constraints but also see to it that the application of sustainable practices is upheld throughout the project lifecycle.

VII. LITERATURE REVIEW

Based on the various reviews on the sustainability integration in railway manufacturing some key studies are reviewed under this section.

In this study by Morin et al. (2025), the railway industry needs the digital transformation to manage the increasing challenges and lead to its sustainable development. “Automatic Train Operation” (ATO) and “Remote Train Control” (RTC) are digital technologies that suggest the possibility to optimize the activities and contribute to their safety. Nevertheless, with both technologies, serious challenges might arise which should be confronted so as to reap the expected benefits in a public street setting within an urban setting. This study therefore comes in to fill the theory practice gap by examining the perceived benefits and obstacles of practicing RTC and ATO using a European public transport operator implementing the technologies in the operations of a tramway. The study utilizes a case study approach based on 44 semi-structured interviews with the stakeholders of the operator and its supplier. The results reveal that the productivity, safety, and sustainability are expected to improve greatly. However, future obstacles like regulatory barriers, technicalities, internal restructuring, etc. limit implementation. The main challenges are to maintain a strong connectivity, making sure that cybersecurity is not a problem, and to take care of the workforce changes. This research highlights the significance of collaborative methods, stakeholder involvement, and gradual implementation to reduce risks and ensure that the effect of automation technologies is maximized [24].

In a study by Lyu and Li (2023), the collection and management a data classification system that has been created based on of basic data to measure railway green performance were considered. A basic database on green performance in a railway has been developed on the basis of data exchange and metadata. There is business, process and entity perspective. It proposes a scheme of extraction of a “Building Information Modelling” (BIM) data model that is based on a field similarity of

matching and a document structure extraction scheme that is based on image recognition. A green performance basic data collection system has been established on railway utilizing a basic data collection system based on green performance that has reached efficiency in the collection and general administration of the railway green performance basic data. Applications such as accounting for CO2 emissions in the railway, green cost-benefit analysis, and consideration of green design solutions could be supported by this system [25].

Table 1 represents the key research studies analyzed in this paper are compared and synthesized, pointing out the areas they focused on, the methods used, the sustainability dimensions, and the contributions made to the knowledge of SP in railway MEP.

Table 1 : Comparative Synthesis

Author(s) & Year	Study Focus	Methodology	Sustainability Dimensions Addressed	Key Findings	Relevance to Railway Manufacturing Engineering
Morin et al. (2025)	Digital transformation and automation in railway operations.	Qualitative case study; 44 semi-structured interviews.	Environmental, operational, and organizational sustainability.	Identified productivity, safety, and sustainability benefits of ATO and RTC, alongside barriers such as regulation, cybersecurity, and workforce adaptation.	Demonstrates how digitalization supports sustainable railway systems while introducing new operational and organizational challenges
Lyu & Li (2023)	Railway green performance data collection and management.	System development; metadata modelling; BIM-based data extraction.	Environmental sustainability, data-driven management.	Developed an integrated railway green performance database supported by BIM, image recognition, and data classification systems; enabled carbon accounting, green cost–benefit analysis, and evaluation of green design solutions.	Provides a digital and data- management foundation for monitoring and evaluating sustainability in railway manufacturing and engineering projects.
Giunta (2023b)	Sustainability trends and challenges in railway infrastructure.	Comprehensive literature review.	Environmental, economic sustainability; lifecycle assessment.	Identified the importance of LCA, circularity metrics, smart monitoring, and sustainable materials in railway tracks and maintenance.	Strongly supports lifecycle-based manufacturing, material selection, and maintenance strategies in sustainable railway engineering.
Ait Ali & Eliasson (2022)	Railway market reorganization and capacity allocation.	Comparative review of European railways.	Economic and social sustainability.	Showed that deregulation outcomes vary widely and that efficient, transparent capacity allocation is still limited.	Relevant to governance and regulatory environments influencing sustainable railway manufacturing and project planning
Økland et al. (2021)	Sustainability evaluation in early phases of railway investment projects.	Mixed methods: interviews, document analysis, case study.	Economic and environmental sustainability.	Found that environmental sustainability is widely considered, but economic sustainability dominates decision-making due to early-phase project structures.	Highlights the importance of early manufacturing and design decisions in shaping sustainability outcomes.

According to Giunta's (2023) study, rail is probably going to be the world's most environmentally friendly mode of transportation in the future due to its high volume and cleanliness. The CO2 emissions and energy use produced by rail is low during operation compared to other modes of transportation, but when building and maintaining it, the environmental impact is intense and must be considered and sufficiently addressed. The proposed research is expected to give a thorough framework of trends and challenges in railway sustainability, with a specific focus placed on track and related materials and components, maintenance strategies, and sustainability assessment methods, by relying on a thorough investigation of the recent literature. The used strategy considers the life of the track and corresponding key phases. This research findings indicate that: (i) a number of innovative sustainable materials have been proposed with high environmental performances and constraints, which are primarily caused by the absence of knowledge of long-term mechanical behavior; (ii) proper maintenance strategies, supported by effective monitoring of the track conditions, could minimize the negative environmental and societal impacts and make this way of transportation more eco-friendly; (iii) numerous devices of the system of the automated tracking of the track defects allow resulting in an increasing number of effective and efficient monitoring of the state of the track and are the key components of the overcoming the challenge of the smart rails [10].

Ait Ali and Eliasson (2022) study, argue that European railways have been restructured to enable market competition. In this way, the train services are no longer vertically integrated with the management of the infrastructure that enables multiple operators to compete. Various means have been developed of vertical separation, capacity allocation and track access charges. In this paper, the author reviews significant elements of deregulation in several countries in Europe. The analysis contrasts the introduction and regulation of competition in terms of describing the allocation of capacity and the track access charges. Despite the fact that the same European legislation was followed, they come to the conclusion that the examined railways have disparate deregulation results, e.g. market organization, capacity allocation. In addition, not many nations have completely succeeded to have transparent and efficient capacity allocation. Though permitted by the legislation, market-based allocation is not present or is never utilized. In order to create more competition that can bring significant social advantages, the survey shows that the majority of European railways are yet to evolve and test more effective and more open capacity allocation processes [26].

The study by Okland et al. (2021) aimed to examine the interpretation and evaluation of sustainability in the initial stages of significant public investment undertakings. These stages are typified by the possibility of highly effective decisions taken before precise detailed knowledge is available. Their study involved combination of qualitative and quantitative sources of information and 3 sets of data; 12 interviews, 10-project railway documents analysis and case study. The qualitative data are semi-structured interviews, whereas the quantitative ones are structured document review of ten Norwegian railway planning documents. Moreover, one of the largest rail infrastructure projects has been done in a case study. The results revealed that various elements of sustainability are considered during the initial stage of investment projects, however, there are no specific demands to conduct a general assessment of sustainability. The respondents are mostly influenced by the environmental aspects of the sustainability concept. Nevertheless, the nature and demands of the initial stages of the national project model guarantees that the economic aspect of sustainability remains the predominant factor in the process of determining what project concepts will be financed to develop further [27].

VIII. CONCLUSIONS

In this review paper, the sustainable practice in railway manufacturing engineering project has been systematically traced through the filter of a broad spectrum of research, generated by manufacturing engineering, railway systems, project management and sustainability-related studies. The review recognizes that sustainability has become a fundamental aspect in the railway manufacturing sector as a consequence of the emerging environmental issues, government limitations, emerging technologies as well as the need to make large engineering projects economically viable in the long term. In particular, the German railway manufacturing industry has been highlighted as a leading example where sustainable practices are being actively implemented.

The literature has suggested that the lifecycle-based design is applied in the manufacturing of railways in the following ways: effective utilization of materials and energy, use of green and digital technologies as well as the incorporation of sustainability concepts into project design and construction operations. The engineering choices of manufacturing considered at the infancy of the project impact strongly on the following environmental performance, the efficiency of running and the costs as the lifecycle of the railway systems. The review also mentions the growing value of digitalization, automation and data-driven tools in meeting sustainability goals as they enable enhancing control over the processes, minimizing waste and making systems more reliable.

Additionally, the assessment notes that the concept of sustainability in railway production includes, not only technical aspects but also supply chain management, stakeholder coordination, and governance. An exceptionally strong liaison

amongst the manufacturers, suppliers, project managers and regulators is highly required to ensure that the sustainable practices are always established and adhered to in the big and sometimes distant situated projects. This has been particularly evident in Germany, where strict regulatory standards and coordinated stakeholder frameworks have driven the adoption of sustainability in railway projects. Overall, it is through sustainable supply chains and stakeholder involvement that transparency, compliance and long-term project success becomes achievable.

However, it is observed that the review still lists the challenges and obstacles that persist and hinder the adoption of SP on a case-by-case basis. Major obstacles to be taken into consideration are technical integration, high initial costs, organizational resistance, incompetent labor force and discrepancies in regulations. These barriers present that sustainability in railway manufacturing engineering projects to be achieved involves technology and organization commitment, supporter and capacity building policies.

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