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Application of Sustainable Infrastructure Criteria in Railway Projects with the Input–Process–Output–Outcome Approach

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ABSTRACT
Present-day societies face unprecedented dependence on built infrastructure amid escalating sustainability challenges including climate change and social inequality. Railway infrastructure, positioned as the most environmentally sustainable transport mode, presents a critical paradox: while essential for sustainable mobility, much of the existing network was built when environmental awareness, accessibility and innovation-driven technologies were not design priorities. This creates a significant research gap in how railway infrastructure can be systematically aligned with current sustainability frameworks such as the UN Sustainable Development Goals (SDGs), Paris Agreement and regional policy initiatives. This study addresses this gap by developing a comprehensive decision-making model that integrates railway-specific sustainability criteria defined in the previous study within an input-process-output-outcome (IPOO) framework. The approach enables infrastructure management organisations to evaluate investment projects beyond immediate operational efficiency, incorporating medium- and long-term impacts that strengthen system resilience. The framework was validated through application to Latvian railway infrastructure investment scenario. Results demonstrate that the IPOO methodology enables infrastructure managers to trace causality from resource allocation decisions through transformation processes to both immediate outputs and long-term societal impacts. Expert panel validation confirmed practical applicability while identifying critical enhancement requirements across all IPOO components. These findings contribute to sustainable infrastructure assessment theory by providing 64 railway sector-specific indicators aligned with broader SDG frameworks. Practically, the model enables railway infrastructure management companies to systematically assess investment projects for medium- and long-term transformative potential, while offering policymakers a structured approach for developing targeted resilience strategies. This research advances the integration of sustainability science with infrastructure decision-making.

KEYWORDS
sustainable infrastructure criteria; railway infrastructure assessment; railway infrastructure planning; IPOO framework.

1. INTRODUCTION

Sustainable and resilient infrastructure stands at the forefront of global policy commitments across organisations such as the Organisation of Economic Co-operation and Development, United Nations, the European Union. However, the existing infrastructure around the world faces at least 15 trillion US dollars investment gap to achieve sustainability and resilience targets [1], while natural disasters in 2024 alone caused losses of 368 billion US dollars [2].

Sustainability is achieved through environmental, social and economic cohesion. However, specific aspects that are important for certain types of infrastructure may slightly differ.

Infrastructure directly or indirectly influences 72% of SDGs targets [3]. Yet the SDGs provide global vision but lack inherent self-sufficiency for all infrastructure types and local contexts. In addition, specific aspects important for certain infrastructure types may differ significantly. Evidence highlights critical needs:

— long-term, adaptable national and local planning to translate SDG targets into actionable infrastructure strategies [4];
— context-specific criteria considering local priorities, environmental conditions and social needs [5]; and
— integrated planning with robust investment governance [6, 7].

Current approaches to sustainable infrastructure criteria application focus on single infrastructure types, e.g. water management systems [8, 9] or transport infrastructure [10, 11]. However, the criteria interactions are not clear or they lack certain community and environmental impacts [12]. While comprehensive frameworks such as FAST-Infra address all sustainability dimensions and project contributions [13], they predominantly examine direct, immediate impacts. Long-lasting systemic changes that make infrastructure accessible to everyone, support communities and transform living environments and standards [14] are often omitted from these frameworks.

Railway infrastructure exemplifies these assessment challenges while serving as a critical enabler of environmentally sustainable transport [15]. Successful railway operations require social cohesion, mobility enablement and contribution to overall societal wellbeing. However, much existing infrastructure was constructed from the mid-19th century onward using standardised principles developed before sustainability became a recognised concept [16, 17]. Contemporary challenges include insufficient electrification, particularly in Eastern Europe, where railways primarily transported bulk goods over long distances [18], inadequate infrastructure and train accessibility [19], lack of innovative solutions enhancing infrastructure resilience and usability [20] and diverse track access charge approaches affecting maintenance opportunities [21]. These limitations highlight a critical research gap: the absence of integrated, long-term evaluation models that apply sector-specific sustainability criteria while systematically connecting immediate infrastructure outputs with transformative societal and environmental outcomes.

Research Gap and Contribution: This study addresses this gap by examining sustainability aspects specific to railway infrastructure and developing a practical IPOO framework for their systematic assessment. The research contributes an integrated evaluation model that enables infrastructure managers to trace causality from resource allocation decisions through transformation processes to both immediate operational outputs and long-term societal impacts, while preserving essential performance requirements.

Research Objective and Questions: The aim of this paper is to develop a comprehensive decision-making framework that bridges immediate infrastructure functionality with transformative sustainability outcomes. The research addresses two fundamental questions:

1) What constitutes an appropriate set of sustainability criteria for railway infrastructure?
2) How can these criteria be systematically incorporated into railway infrastructure planning to achieve medium- and long-term sustainability and infrastructure resilience through structured causality chains?

The answers to these questions support development of a decision-making model for railway infrastructure planning and management. At the same time, they provide foundations for sustainable infrastructure planning applicable to other infrastructure sectors.

The remaining paper is structured as follows: Section 2 details methodology; Section 3 presents work on criteria application to the railway sector and the related indicators; Section 4 discusses further elaboration to define a clear-cut infrastructure planning model. Four annexes with railway-specific indicators are appended to this publication.

2. METHODOLOGY

This section explains the methodology used to categorise, assess and apply sustainable infrastructure criteria to railway infrastructure. It is based on the IPOO framework.

2.1 Overall framework

This study implements the IPOO framework considering both immediate effects and long-term transformative impacts. This model is often used in policy analysis, project management and impact assessment due to its clear logic and effectiveness in linking resources to change.

This framework originates from foundational input–output model formulated by Leontief [22] to represent economic interdependencies between different sectors, tracing flows of resources and outputs across an economy and allowing gross domestic product calculation. In management science, the input–process–output (IPO) model describes how inputs (resources and conditions) are transformed through processes into outputs (results and products). Finally, by the late 20th century, the framework was extended with the addition of outcomes, capturing not just immediate results (outputs), but also the longer-term effects and changes resulting from an intervention or system (IPOO). Further refinement of the framework includes results chains in development and OKRs (objectives and key results), introducing indicators at each stage for transparent monitoring and evaluation. Research highlights that the IPOO framework overcomes the limitations of models focusing only on short-term outputs by capturing the full chain from resource allocation to ultimate impact and providing a multidimensional and reliable tool for sustainability evaluation [23].

This study develops an IPOO methodology for decision-making in railway infrastructure planning. The framework operationalises sustainability criteria identified through systematic literature review conducted by the authors and described in previous articles. In previous stages of this multi-step research, 43 sustainable infrastructure criteria most frequently mentioned in scientific literature were consolidated into 18 broader categories [24]. Now they are supplemented with indicators relevant to the railway sector identified by scoping review (described further in this section). The criteria were reframed according to IPOO, establishing four interconnected components operating across multiple temporal and spatial scales (*Figure 1*).

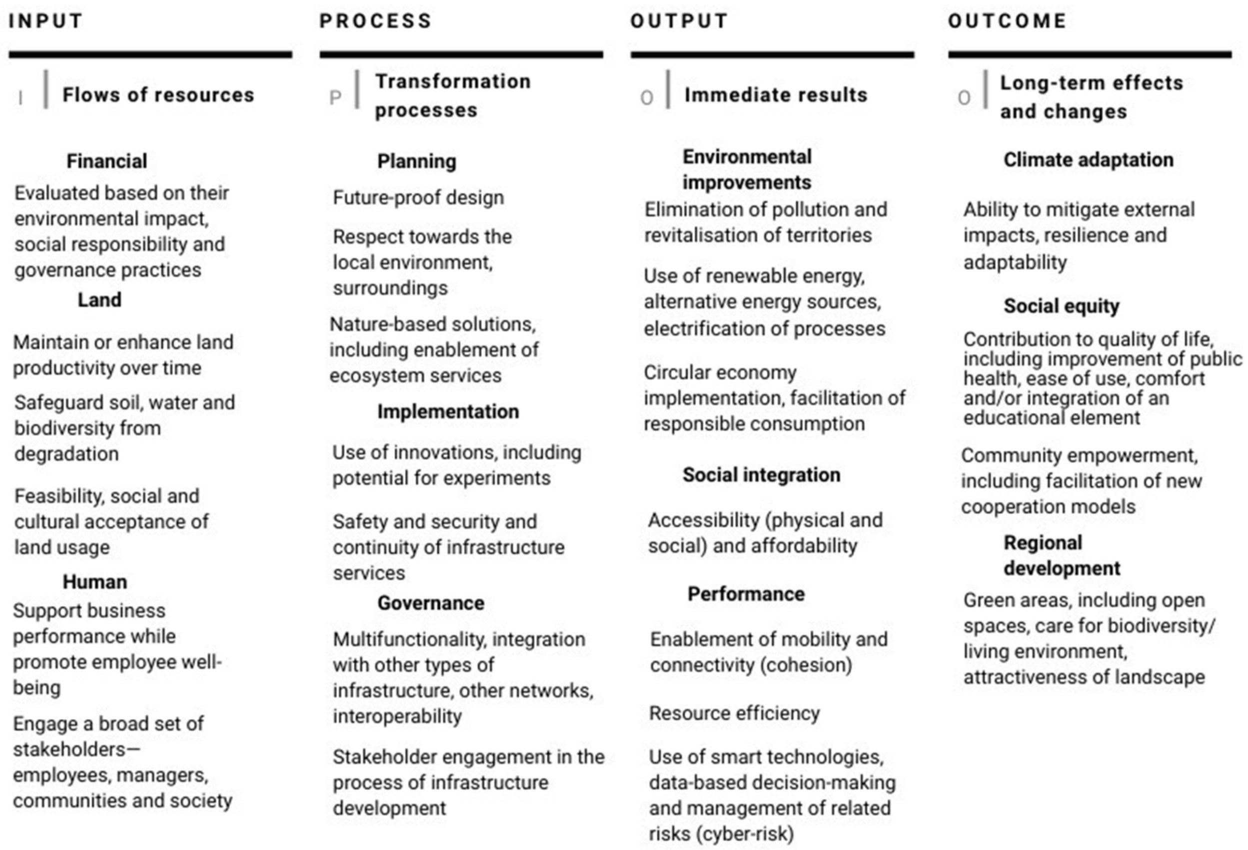

Figure 1 – Conceptual framework of the IPOO methodology integrating sustainability criteria for railway infrastructure planning, based on [25]

The IPOO framework consists of:

- Inputs incorporating flows of resources including financial allocation, land management and human resources;
- Processes representing transformation mechanisms comprising planning procedures, implementation pathways and governance structures;
- Outputs capturing immediate results across environmental improvements, social integration and infrastructure performance including innovation implementation;
- Outcomes assessing long-term effects including climate adaptation, social equity and regional development.

In developing the framework, it became evident that IPOO may overlook integral features of existing railway infrastructure, such as capability, safety, punctuality and flexibility. These criteria remain essential for railway but risk being deprioritised when focusing on future developments, particularly during infrastructure rebuilding. This gap will be eliminated in Section 2 and discussed in Section 3.

The framework was subsequently equipped with specific measurable indicators identified through scoping review, as detailed in the following subsection.

2.2 Scoping review

To operationalise the IPOO framework, specific indicators were identified through a systematic scoping review of SCOPUS database publications from 2020 to 2025 (Q1-Q2 journals). The review employed targeted search strategies combining "railways" with each of the 18 sustainable infrastructure criteria categories provided in *Figure 1*. Each indicator for each category was systematically assessed through four evaluation dimensions with a common goal "to effectively translate the theoretical IPOO framework into practical decision-making tools for railway infrastructure planning, ensuring both scientific rigor and operational applicability". All inconsistences were discussed with the research group:

- Adequacy – coverage of relevant aspects within each criterion, ensuring indicators capture the scope of the sustainability dimension.
- Quality – measurability and precision of indicators, prioritising quantitative metrics with clear units of measurement.
- Timeliness – indicators reflect present-day railway infrastructure challenges and technological capabilities.
- Long-term availability and commitment – feasibility of consistent data collection and institutional capacity to maintain indicator measurement over extended periods, supporting longitudinal assessment and monitoring capabilities.

The data that support the findings of this scoping review are available on request from the corresponding author. The authors acknowledge that the selection of indicators for infrastructure development may differ across studies depending on regional challenges, the stage of existing infrastructure development and other contextual factors. They may reflect the unique circumstances of different regions and development contexts; however, the underlying principles remain the same.

2.3 Case study

To validate the practical applicability of the IPOO framework, a retrospective case study was conducted as a structured thought experiment, analysing the European Union-funded railway infrastructure modernisation project in Latvia. The case study focused on the passenger platform modernisation at 16 stations along the Rīga – Tukums line, which represents one of Latvia's most actively utilised passenger railway corridors, connecting the capital to a major resort destination while serving critical daily commuting functions. This project was selected for analysis due to its: (1) clear temporal boundaries and documented outcomes, (2) strategic importance as an EU-funded infrastructure intervention, (3) multi-dimensional impact covering economic, social and environmental domains and (4) sufficient time elapsed (2013–2025) to assess both immediate outputs and longer-term outcomes.

The thought experiment involved imagining scenario of the implications of theoretical framework without physical experimentation firstly. This was adopted through systematic evaluation of the actual project implementation through the IPOO lens, identifying good practices and implementation gaps across the four framework components. Historical project documentation, performance data and post-implementation assessments were analysed to map actual project elements against IPOO sustainability indicators. This part does not generate new empirical data; instead, it provides logical reasoning, internal consistency and the manipulation of hypothetical criteria and indicators [26, 27]. The analysis examined the 12-year period (2013–2025) to capture both immediate project outputs and evolving societal outcomes, enabling assessment of the framework's potential for bridging short-term interventions with long-term sustainability objectives.

Finally, as the conclusions require empirical testing for scientific validation [28], an expert panel discussion was conducted to evaluate the proposed IPOO framework improvements and validate the thought experiment findings. The expert panel methodology was designed to bridge the gap between theoretical framework development and practical implementation requirements through structured professional assessment.

The significance of the expert assessment lies in its role as an external validation mechanism bridging the theoretical development of the IPOO framework with real-world infrastructure management practice. It served to test the operational feasibility of the framework, to identify gaps not visible from a purely theoretical perspective and to verify whether the proposed indicators and causal logic are suitable for application in actual investment decision-making.

A purposively selected panel of six experts was assembled, representing diverse but complementary expertise areas: railway infrastructure experts engaged in project implementation (2 experts), sustainability expert (1 expert), financing expert (1 expert) and external stakeholders – mobility expert and a non-governmental organisation (NGO) representative involved in infrastructure projects (2 experts). Selection criteria included: (1) minimum 5 years of relevant professional experience, (2) documented involvement in railway infrastructure projects, (3) familiarity with sustainability assessment frameworks and (4) experience with decision-making processes, that involves stakeholder consultation.

The expert evaluation was conducted as a structured qualitative expert panel validation method using a two-stage structured discussion process. In the first stage, experts individually reviewed the case study analysis and proposed IPOO improvements, providing written assessments focusing on framework's applicability, implementation feasibility, clarity of the IPOO logic and the relevance of the proposed sustainability indicators. In the second stage, a facilitated group discussion session examined areas of consensus and divergence, focusing on: (1) practical viability of proposed input, process, output and outcome improvements, (2) potential implementation barriers and enablers, (3) framework scalability across different railway infrastructure contexts and (4) integration requirements with existing regulatory and organisational frameworks.

Expert feedback was subjected to systematic qualitative thematic analysis, and the results directly informed the refinement of the IPOO framework. As a result of the expert assessment, several framework improvements were introduced, including:

— clearer differentiation between short-term outputs and long-term societal outcomes,
— the explicit reintegration of core railway performance parameters (such as safety, capacity and punctuality) into the sustainability structure and
— adjustments to governance- and financing-related indicators to better reflect real institutional constraints.

Most of the experts required anonymity of their statements.

The results are discussed in the following sections to address the research questions.

Considering the study covers part of more extensive research, *Figure 2* exhibits the methodology and structure of this study in the broader sense.

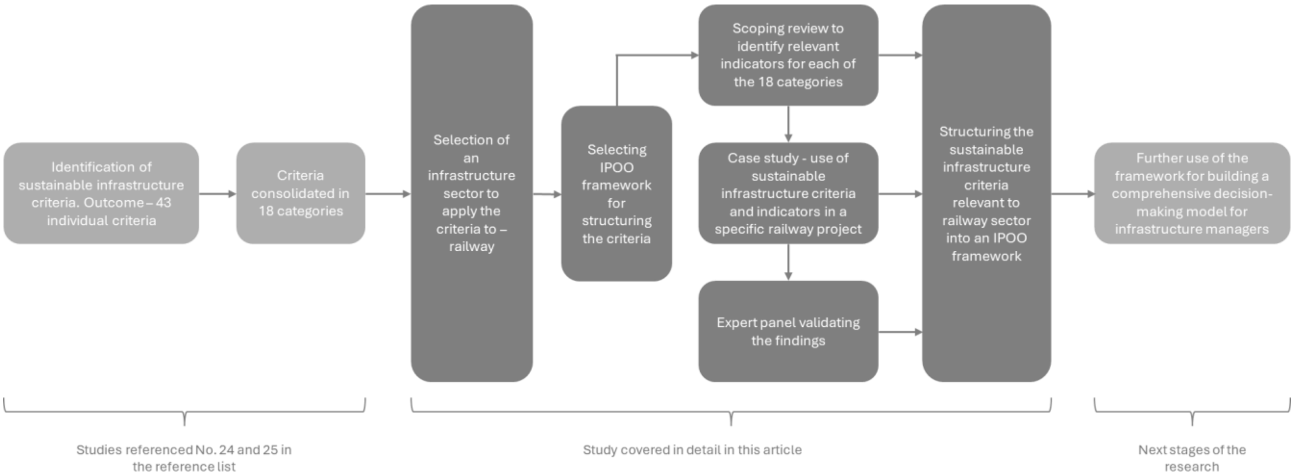

Figure 2 – Scope and methodology of the study

3. KEY RESULTS

This section addresses both research questions. It presents the results of a scoping review on sustainable infrastructure indicators that constitute appropriate criteria for railway infrastructure. Further, it illustrates how these indicators, structured within the IPOO framework, can be effectively incorporated into railway infrastructure planning to achieve medium- and long-term sustainability, as demonstrated through a case study.

3.1 Results of scoping review

The practical implementation of sustainability criteria in infrastructure planning requires clearly defined, measurable indicators that enable objective assessment of criterion fulfilment. While the fundamental sustainability principles remain consistent across infrastructure types, their specific indicators necessarily vary according to sector-specific operational characteristics and performance requirements. For example, railway infrastructure sustainability indicators differ from those applicable to district heating or water supply systems. To bridge this gap between theoretical sustainability frameworks and practical railway infrastructure assessment, a targeted scoping literature review was conducted. Empirically validated indicators were identified that operationalise the sustainable infrastructure criteria established in the previous section for the railway infrastructure case study. The results are presented in *Annex 1–4*.

Annex 1 presents the input-specific indicators identified through the scoping review. As concluded in previous research, infrastructure companies, which are usually state or municipality-owned, typically have resource flows already covered by sustainability reporting [25]. For instance, in the European Union, financial criteria are defined by the EU Taxonomy Regulation [29]. Human capital indicators that emphasise stakeholder engagement, employee welfare and community integration are also widely employed by modern human resource management practices. However, land-related indicators that address productivity, environmental protection and social acceptance are rarely introduced and are therefore proposed based on the FESLM framework [30]. These input indicators establish the baseline requirements and resource considerations that must be evaluated prior to railway infrastructure implementation. They form the foundation upon which the subsequent processes of procurement and transformation of existing infrastructure will be performed.

Annex 2 presents process-specific indicators covering planning, implementation, safety and governance aspects of processes, capturing how resources are transformed into sustainable infrastructure outcomes. The IPOO framework emphasises that sustainable infrastructure depends not only on adequate inputs and final outputs, but on the quality of transformation processes that govern resource utilisation, stakeholder engagement and operational implementation. Monitoring these processes practically requires actionable instructions with specific performance indicators. That helps infrastructure managers optimise resource allocation and ensure development activities align with long-term sustainability objectives.

Annexes 3 and 4 present output and outcome indicators within the IPOO framework. The indicators demonstrate that some criteria are relatively technical and can be achieved in the short to medium term by railway infrastructure management companies themselves, provided they have sufficient resources. In contrast, other indicators represent long-term outcomes of strategic railway development that generate external effects. These indicators typically require engagement with external stakeholders to achieve.

Short- to medium-term actions that lead to measurable positive effects include immediate improvements in connectivity, reduced energy consumption etc. These outputs can be directly controlled and implemented by infrastructure management companies through technical improvements and operational changes. Conversely, long-term outcomes such as quality-of-life improvements, community empowerment or increase in overall resilience of infrastructure represent complex effects. They extend beyond the direct control of infrastructure management companies while remaining dependent on their strategic actions.

Through the systematic listing and analysis of sustainability criteria, the authors identified a critical gap of IPOO framework: sustainability frameworks often overlook fundamental performance indicators that have been well-established and achieved in previous decades of infrastructure development. For railway infrastructure, these essential performance dimensions must include at least capability, punctuality, safety and flexibility. Those are core operational characteristics that define effective railway systems regardless of sustainability considerations. Otherwise, there is a risk of “throwing the baby out with the bathwater” or discarding proven performance metrics along with outdated practices. To address this limitation, the IPOO framework requires enhancement through an additional layer of integral indicators that capture the inherent operational features specific to each infrastructure type. These integral indicators ensure that fundamental infrastructure performance characteristics are preserved and measured alongside sustainability criteria. Thus, the loss of essential functionality in the pursuit of broader sustainability objectives is prevented.

The provided set of IPOO-structured criteria, enhanced with performance indicators, constitutes an appropriate framework for sustainable railway infrastructure management. It can be applied both for evaluating the implementation of individual infrastructure projects and as a selection methodology when proposed projects exceed available financing capacity. Next subsection demonstrates how application of the sustainable infrastructure criteria may create medium-term tangible benefits as well as long-lasting fundamental changes to the society and the environment, thus contributing to the global sustainability goals.

3.2 Results of the case study

To demonstrate practical framework application, this study examines a railway infrastructure project in Latvia, where the state-owned railway infrastructure management company uses EU funding for passenger infrastructure modernisation [29]. The project targeted modernisation of passenger platforms at 16 stations, primarily along the Rīga – Tukums line, which is one of Latvia's most actively used routes connecting the capital to a major resort Jurmala while serving daily suburban commuters.

Putting this project into perspective of the IPOO framework, it is structured as provided in *Table 1*, where outputs and outcomes are primarily viewed through the lens of sustainable infrastructure criteria identified in the previous sections and are highlighted in *italic*.

Table 1 – IPOO framework applied to railway passenger platform modernisation project

Input	Process	Output	Outcome
Financial: The project is financed by the EU funds. They are not guaranteed for the next phases of the project, and the company needs to consider new financial sources. The project is eligible and potentially aligned with the EU Taxonomy requirements as noted in Section 3.1. **Land:** The infrastructure is developed within the boundaries of the existing railway infrastructure. No additional land resources are required or used. Thus, the criteria and indicators listed in Section 3.1. are not applicable to this project. ***Human resources*:** The company has a Project Management Division in charge of project development and coordination. Other business units are engaged in coordination of certain elements (e.g. electric systems). External subcontractors that are engaged in implementation of the project are also engaged in project planning. Job security, overall satisfaction for development of modern infrastructure are observed.	**Planning process:** A technical project and project management plan is being developed. Internally developed UX standard [30] ensures that all modernised platforms are built in a unified manner. Implementation of the UX standard is included in project supervision controls, fulfilling *future-proof design* considering design, materials, weather impact on station amenities, service of different current and future passenger groups, etc. *Respect towards the local environment* is considered preserving the historical station buildings. *Nature-based solutions* are not specifically considered. **Implementation process:** *Innovations and experimental features* are not at the core of this project. *Safety* is an integral part of any railway infrastructure project and considered for passenger specific features (e.g. to build ground level markups for people with eyesight impairments etc.). **Governance process:** *Interoperability* is ensured through coordination with passenger carrier companies and their fleet renewal plans. They need to be compatible with infrastructure development. *Stakeholder engagement* is organised as consultations with an NGO specialised in disabled people rights and needs. Those are implemented and thus cover the interests of the most vulnerable passenger group.	**Environmental improvements:** *Elimination of pollution* is not an output of this project. *Electrification* is additional side-factor to the project but not specifically measured for this project. The UX standard includes suggestions on materials that need to be used in station equipment – including materials that are resilient towards external impact (e.g. vandalism). However, it does not require applying *circularity principles* such as use of recycled materials. **Social integration:** The project includes a set of features that improve the possibilities for disabled passengers as well as elderly people (*accessibility*). For example, they are equipped with special markups on the ground level and improved electronic tableaus visible for people with eyesight impairment. Measurable indicators for this output: number of stations across the Latvian railway network accessible for disabled people (passengers with restricted mobility or PRM). **Performance:** Railway transportation in general becomes more *accessible* for diverse groups of people. The project includes development of certain multi-*mobility features*, e.g. bicycle storage etc. Measurable indicators for this output: increase in number of passengers in railway lines which have been modernised. UX standard decreases total cost of ownership (TCO; leading to *resource efficiency*), providing unified types of materials used, less energy resources spent to produce and transport the materials, etc. Measurable indicators for this output: decrease of material costs, time spent on approvals (however, these indicators may be only measured against previous comparable experiences). The project also includes certain *smart technology* features, such as use of intelligent information systems for passenger announcements. This was not a direct output of this project. Measurable indicators for this output: not specifically measured for this project.	**Climate adaptation:** *Resilience* of the infrastructure is partly achieved, as weather impacts are included in the UX standard. Measurable indicators for this outcome: registered incidents (or their decrease if the company has comparable data) on weather-induced damage to passenger infrastructure in modernised vs non-modernised stations. **Social equity:** The society's *quality of life* is achieved through more accessible infrastructure, etc. *Community empowerment* is achieved allowing more distanced work or study options than a person would have considered before. These outcomes are expected to be achieved in combination of the project that increase maximum speed for the trains. Measurable indicators for this outcome: employment level increase across cities / regions with modernised railway infrastructure; social mobility indicators (daily commute data). **Regional development:** The project does not contribute to creation of new *green areas*, but it improves the overall *landscape attractiveness* in the respective areas, as the new stations are visually more appealing. Measurable indicators for this outcome: increase of the local area which is attractive for the local community and visiting people.

Retrospective application of the IPOO framework shows that the specific railway project does not exhibit all sustainable infrastructure criteria considered in the previous section. However, it clearly shows that a certain project may achieve both medium-term tangible outputs and long-term more fundamental outcomes for the society. Also, the framework clearly indicates that the priority of outputs and outcomes relevant to a specific infrastructure may change from project to project. For example, if the case study would cover railway electrification, the sequence and significance of the outcomes would be different, although all of them are still relevant.

It is important to note that there are several sustainable infrastructure criteria which exhibit themselves not as outputs or outcomes but rather as process components. For example, stakeholder engagement and future-proof design development which need to be in place before the actual implementation of the project starts (but they are not mandatory compared to the next two criteria mentioned below).

There are two sustainable infrastructure criteria which are currently included in the process section, although they are fundamentally important and all-encompassing for the railway sector (and required by external regulations) – safety and interoperability. These criteria may not be called neither inputs, outputs nor outcomes as they are not achieved through implementation of the project. But they are an integral part of railway infrastructure and may not be neglected at any phase. The approach for their integration in the IPOO framework will be further considered in the discussion section.

3.3 Lessons learned from case study and required improvements in IPOO framework

Input

Expert panel evaluation revealed critical implementation gaps in the IPOO framework's input phase despite acknowledging strong EU taxonomy alignment:

— Panel members identified technological resource planning as the most significant improvement opportunity, noting insufficient attention to technological aspects. Experts emphasised that human capital allocation requires enhancement through targeted training programs for contractors, extending input planning beyond capability development.
— Expert feedback highlighted time and scheduling commitments as underestimated input factors, particularly for infrastructure projects requiring operational modifications. The panel noted that the framework inadequately addresses how scheduling decisions cascade through processes and directly impact short-term accessibility and efficiency outcomes.
— Experts identified the need for stronger integration of stakeholder engagement strategies with risk assessment protocols. Currently they are treated as separate actions rather than interconnected strategic components.

Expert panel consensus concluded that IPOO input phase effectiveness requires more holistic resource planning, improved temporal impact assessment and strengthened governance transparency mechanisms. In the case study those are partly covered with UX standards, but that may not be applicable in other situations.

Process

Analysing the process phase through practical application shows structural weaknesses that undermine the IPOO framework's effectiveness in managing complex infrastructure projects. These deficiencies express across planning, implementation and governance processes, suggesting systemic rather than isolated improvement needs:

— The most critical deficiency lies in the absence of integrated sustainability assessment procedures coupled with robust multi-criteria decision analysis protocols. Current application demonstrates that conflicting criteria prioritisation cannot be adequately resolved without systematic stakeholder consultation and co-creation mechanisms.
— Quality assurance and monitoring systems remain inadequately integrated with knowledge transfer mechanisms from connected infrastructures (energy, municipal green zones) and users (passengers).
— Innovation integration presents challenges, as current processes lack established experimentation protocols and validation procedures adapted to specific operational conditions.
— Cross-sectoral coordination mechanisms suffer from insufficient advisory body integration, while regulatory compliance monitoring lacks the continuity of complex, multi-year projects. Most critically, stakeholder engagement processes demonstrate poor continuity management, with inadequate feedback loops and learning systems that prevent adaptive management throughout project lifecycles.

The process phase effectiveness requires integrated assessment protocols, systematic knowledge management and continuous stakeholder engagement mechanisms that maintain coherence across extended implementation timelines.

Output

The expert panel reached several critical conclusions regarding output measurement and management within the IPOO framework. They highlight both strengths and systematic deficiencies in current approaches to sustainable railway infrastructure assessment:

— The panel concluded that IPOO did not cover criteria where project output demonstrated strong competency in measuring and achieving traditional performance outputs, particularly safety and security improvements through accident reduction, punctuality metrics, etc.
— Experts identified significant deficiencies in managing trade-offs between environmental outputs and operational efficiency. Current frameworks inadequately address situations where environmental improvements may compromise traditional performance metrics, lacking systematic approaches for optimising the competing objectives.
— The panel highlighted a fundamental asymmetric information problem in social integration outputs. Social partners responsible for accessibility, connectivity and stakeholder satisfaction recommendations rarely face accountability for implementation outcomes. The experts suggested that comprehensive process documentation and clear accountability mechanisms for social partners represent essential framework improvements.
— Experts emphasised that innovation outputs cannot be treated as straightforward performance metrics but require sophisticated risk assessment and mitigation strategies to ensure successful integration with existing infrastructure systems.

Outcomes

The expert panel, reaching significant consensus about outcome measurement capabilities and long-term impact assessment within the IPOO framework:

— The panel validated observable economic outcomes, particularly the documented 30% passenger increase on the modernised line, as evidence of successful regional connectivity enhancement and service demand stimulation.
— Experts reached consensus on critical deficiencies in social assessment, concluding that quality of life enhancement, educational and cultural benefits and social equity improvements remain systematically unmeasured despite their potential significance.
— Regarding environmental impacts, experts acknowledged that the infrastructure operates with reduced environmental impact compared to alternative transport modes. At the same time, comprehensive environmental outcome assessment remains undocumented and methodologically underdeveloped.

The panel reached unanimous conclusions regarding fundamental deficiencies in impact assessment methodology, particularly emphasising the systematic absence of longitudinal studies, comparative baseline scenarios and economic valuation of non-market benefits.

4. DISCUSSION AND CONCLUSIONS

This study addressed a critical gap in sustainable infrastructure assessment by developing an integrated IPOO framework specifically designed for railway infrastructure planning.

The systematic scoping review identified and operationalised 64 railway sector–specific indicators for sustainable infrastructure criteria, organised within the IPOO framework, thereby creating a comprehensive assessment tool for railway infrastructure. The enhanced framework incorporates traditional performance indicators (capability, punctuality, safety, flexibility) alongside sustainability metrics, preventing the risk of missing inherent features when pursuing sustainability goals. This approach ensures that fundamental infrastructure performance characteristics are preserved while advancing toward broader sustainability objectives.

The framework successfully demonstrates how sustainability criteria can be systematically incorporated into railway infrastructure planning through structured input-process-output-outcome chains. The case study validation revealed that the IPOO methodology enables infrastructure managers trace causality from resource allocation through transformation processes to both immediate outputs and long-term impacts, supporting evidence-based decision-making across multiple temporal horizons.

The study's methodological approach combines systematic literature review, structured thought experimentation and expert panel validation to bridge theoretical framework development with practical implementation requirements. The thought experiment methodology proved effective for retrospective assessment and alternative scenario development, though the panel emphasised that empirical validation remains necessary for full scientific validation.

A key limitation identified through practical application is the framework's initial inadequacy in addressing integral infrastructure characteristics that cannot be classified as project outputs or outcomes but represent essential operational requirements. The proposed enhancement through an additional layer of integral indicators addresses this deficiency while maintaining framework coherence.

The IPOO framework provides infrastructure management organisations with a comprehensive decision-support tool that enables assessment of investment projects beyond immediate efficiency considerations to encompass medium- and long-term transformative impacts. The methodology's integration with existing environmental assessment procedures ensures compatibility with established governance frameworks while extending evaluation scope to comprehensive sustainability outcomes.

Other methodologies developed for railway infrastructure sustainability assessments – for example, a three-tier network modelling roadmap for assessing railway resilience [31], mega-infrastructure development assessment [32] or computational analysis on material use in railway [33] – cover only specific aspects of railway infrastructure development. Compared to those, use of the IPOO framework allows using a holistic approach equally assessing all sustainable infrastructure aspects in one model.

For policy makers, the framework offers structured approaches to project prioritisation and resource allocation when proposed infrastructure investments exceed available financing capacity. The systematic consideration of stakeholder engagement, future-proof design and long-term outcome tracking supports evidence-based infrastructure planning that aligns with global sustainability commitments including the United Nations Sustainable Development Goals.

The research establishes foundations for multi-criteria decision-making model development that considers temporal progression through IPOO framework levels. Future research should focus on developing quantitative weighting mechanisms for competing criteria, establishing standardised protocols for long-term outcome assessment and testing framework applicability across diverse infrastructure sectors and contexts.

The identified need for dynamic criteria evolution frameworks suggests important research opportunities in developing adaptive assessment methodologies responding to changing sustainability priorities, technological developments and emerging challenges such as climate resilience and digital infrastructure integration.

This study contributes to broader sustainable infrastructure research by demonstrating that comprehensive sustainability assessment requires systematic consideration of resource inputs, transformation processes, immediate outputs and long-term societal outcomes. The enhanced IPOO framework successfully integrates traditional infrastructure performance requirements with contemporary sustainability objectives, providing a basis for a practical tool for infrastructure managers and policy makers to support evidence-based decision-making that addresses both regulatory requirements and emerging sustainability challenges.

The framework's validation through real-world application confirms its utility for bridging short-term project interventions with long-term sustainability objectives. Expert panel assessment provides clear directions for methodological refinement and enhanced implementation effectiveness. The research establishes a foundation for sustainable infrastructure planning that maintains operational excellence while advancing comprehensive sustainability goals, supporting the global transition toward resilient and sustainable infrastructure systems. The results of this study will be further used to develop a comprehensive decision-making model for infrastructure managers.

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Annex 1 – Input specific indicators

Criterion	Indicators	Sources
Financial		
Evaluated financial products based on their environmental impact, social responsibility and governance practices	An economic activity supported by investment: (a) contributes substantially to one or more of the environmental objectives, (b) does not significantly harm any of the environmental objectives, (c) is carried out in compliance with the minimum safeguards.	[1]
Land		
Maintain or enhance land productivity over time	Cropping intensity, nutrient budgets, bio productivity	[2]
Safeguard soil, water and biodiversity from degradation	Soil erosion, soil organic carbon content, soil nutrient balance, land degradation, biodiversity, water resources	
Feasibility, social and cultural acceptance of land usage	Land tenure and ownership security, regional poverty, employment, cultural and recreational values	
Human		
Support business performance while promote employee well-being	Compliance with equality policies and labour laws Ensure employee health and safety standards Job security and turnover rates Fair wages and benefits	[3]
Engage a broad set of stakeholders – employees, managers, communities and society	Employee engagement and satisfaction levels Equal opportunity employment measures	

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Annex 2 – Process specific indicators

Criterion	Indicators	Sources
Planning process		
Future-proof design, including consideration of future renovation needs and potential risks	Highly related to several of the criteria and indicators above – e.g. timely identification and management of climate risks, risks related to smart technology use and others	[1, 2, 3]
Respect towards the local environment, surroundings	Adjustments or changes made to a project to encompass local specificity Number or area of sensitive territories affected Improvement of local accessibility	[4, 5, 6]
Nature-based solutions, including enablement of ecosystem services	Incorporation of nature-based biodiversity-related solutions in railway infrastructure management (although identified as a separate criterion before, here works as a factor for better quality of life in urban areas)	[7]
Implementation process		
Use of innovations, including potential for experiments	Existence of open culture and supporting business processes (e.g. tendering processes) Gradual development of innovations and related capabilities (from easier to more complicated solutions) Use of innovative materials in railway construction Use of smart technologies as listed in the table above	[8, 9, 10]
Safety and security and continuity of infrastructure services	Track geometry defects, leading to rail track corrugation, broken rails, etc. (number of events, length of defects or specific measurements indicators) Signal and other communication delays (e.g. delay time or percentage of events) Broken bolts, defective switches and other technical elements Vehicle hunting due to faulty tracks (number of cases; frequency of increased vibration) Emergency response time Number of railway accidents (due to faulty infrastructure)	[11, 12, 13, 14]
Governance process		
Multifunctionality, integration with other types of infrastructure, other networks, interoperability	Number of integrated services between railway and other transport modes Number of connections with other transport modes and/or regions, countries Existence of cross-systems integrations	[15, 16, 17, 18]
Stakeholder engagement (in the process of infrastructure development, definition of the stakeholders' needs, etc.)	Decreased legal, administrative and other costs Increased community and/or customer satisfaction with the developed solution Identification of add-ons for the project that create additional value and benefit and/or minimise risks (e.g., safety risks) Timely identification of changes that should be made to the initial project	[19, 20, 21, 22, 23]

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Annex 3 – Output specific indicators

Criterion	Indicators	Sources
Environmental improvements		
Elimination of pollution and revitalisation of territories	Area or percentage of a treated territory with water pollution, soil pollution or erosion and/or untreated waste Decrease in noise level (dB), decrease in affected territories / communities	[1]
Use of renewable energy, alternative energy sources, electrification of processes	Degree of electrification of total main track Use of alternative energy sources Proportion of renewable energy used; use of energy storage systems	[2, 3, 4, 5]
Circular economy implementation, facilitation of responsible consumption	Reuse of materials (per volume) Use of materials with lower greenhouse gas emissions as traditional alternatives Proportion of recycled materials / secondary materials Decrease of waste	[6, 7, 8, 9]
Social integration		
Accessibility (physical and social inclusivity) and affordability	Ease of use of a specific service Physical accessibility for disabled, elderly, etc. people	[10]
Performance		
Enablement of mobility and connectivity (cohesion), including green mobility	Number of connections (with the same or different transport mode) Average connection time Travel time	[10]
Resource efficiency, including a decrease in use of energy resources, which may result in decreased emissions	Total cost of ownership (EUR/km of tracks) Energy and fuel consumption Decrease in energy and fuel consumption; decrease in related GHG emissions	[7, 11, 12]
Use of smart technologies, data-based decision-making and management of related risks (cyber-risk)	Use of sensors to control diverse infrastructure variables Use of diagnostic tools, including on-board measuring devices Use of automated problem-solving solutions Use of AI-based recognition systems for railway safety improvement Use of smart energy management systems Use of climate hazard and other prediction tools	[3, 7, 13, 14, 15, 16]

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Annex 4 – Outcome specific indicators

Criterion	Indicators	Sources
Climate adaptation		
Ability to mitigate external impacts (incl. climate change impacts), resilience and adaptability in the medium-term	Amount of economic loss (financial losses) Functionality recovery time Introduction of solutions which decrease the probability of damage and loss	[1, 2]
Social equity		
Contribution to quality of life, including improvement of public health, ease of use, comfort and/or integration of an educational element	Increase in number of inhabitants in suburban and rural areas Increase in property prices and occupation rates (due to better connection and/or decrease in negative side-effects of railway operations such as noise) Transformation of railway stations into public spaces and hubs	[3, 4, 5, 6, 7]
Community empowerment, including facilitation of new cooperation models	Increase in local business activity and income	[8]
Regional development		
Green areas, including open spaces, care for biodiversity/living environment, attractiveness of landscape	Species population and richness around railway Vegetation intensity / area	[9, 10]

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