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Barriers and Challenges to the Circular Economy Paradigm Shift in the Swedish Railway System

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Waste reduction and reduced environmental impacts are the aims behind the European Union's accelerated paradigm shift toward a circular economy. Although the transport industry is an important sector, limited applications and implementations of the circular economy have been reported in the railway industry. To accelerate the transition, potential barriers that slow down the implementation process should be identified and addressed.
This study consists of a structured questionnaire followed by an interview, which focuses on identifying and evaluating the importance of circular economy implementation barriers for the Swedish railway system. The study shows that different organizations include circular economy implementation in their future plans. Meanwhile, the experts highlighted that the current business model, economic competitiveness of virgin materials, logistical challenges, and regulatory inconsistencies slow down the transition process.
The pillars of system innovation and implementation have been analyzed, and the results show that "Business models, investments, and procurement" are the most important pillar category, followed by "Infrastructure". The results also show that the prominent barriers are "Market price advantage of virgin materials", "Lack of supply chain integration", "Storage and site limitations", and "Complexity of wide-ranging products and volumes reaching End-of-Life". These barriers highlight that the economic competitiveness of virgin materials, logistical challenges, and regulatory inconsistencies are the most prominent issues.
Keywords: Circular Economy, Sustainability, Railway System, Barriers Analysis

1. Introduction

The European Union is accelerating a transition to the circular economy (CE) to reduce waste and its environmental impacts. Unlike the traditional linear model of "take–make–dispose", CE promotes a fundamental shift towards a more sustainable approach (Ellen MacArthur Foundation 2013). The construction sector in Europe produces more than 0.8 billion tons of waste, accounting for around 38% of the region's total waste, which brings CE into consideration (Waste statistics 2024). CE also plays a crucial role in reducing carbon emissions and is considered an effective strategy for reaching net-zero greenhouse gas (GHG) targets and addressing climate change.

The circular economy is "an economic system that uses a systemic approach to maintain a circular flow of resources by recovering, retaining, or adding to their value while contributing to sustainable development" (O'Leary, Osmani, and Goodier 2024). CE contributes to increased sustainability by reducing carbon emissions, environmental degradation, and virgin materials usage.

CE strategies can be implemented and assessed at different levels. Some scholars describe three primary levels that consist of Micro, Meso, and Macro levels ranging from product level to national economic scales (De Abreu et al. 2022); Dos Santos et al. 2022; Kristensen et al. 2020).

The implementation of CE requires the development of structured frameworks and the identification of key performance indicators (KPIs) (Muñoz, Hosseini, and Crawford 2024). Material Flow Analysis (MFA) and Resource Flow Analysis (RFA) are the primary methods used in CE, while complementary tools such as Life Cycle Assessment (LCA) can also be applied. These additional approaches help evaluate sustainability by incorporating social, environmental, and economic dimensions. Frameworks and strategies addressing the core elements of CE in various research projects often have foundational similarities, though their terminology may differ. Two prominent CE frameworks are R-frameworks (different CE strategies including Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) (Esther Goodwin Brown et al. 2021) and the Flow Framework (Bocken et al. 2016). Both frameworks provide structured approaches for applying circular economy principles, even though they emphasize different aspects of resource management and sustainability. These frameworks and KPIs facilitate the implementation of CE strategies. However, the limited number and lack of full implementation of CE practices in the railway system reveal that there are barriers that slow down the implementation process and should be identified and addressed.

Barrier analysis for CE implementation has been conducted in different contexts, from general to specific sectors, using different approaches, including survey, literature review, interview, and questionnaire. In a general look at CE barriers, it is assumed that technological barriers are the main issues in CE implementation, but an EU-wide evidence study revealed that cultural barriers, such as lack of awareness and consumer demand, are the main barriers (Kirchherr et al. 2018). Grafström and Aasma (2021), after thoroughly reviewing the CE barriers, listed some of the most cited barriers, which belong to the institutional and cultural category, and mentioned inconsistent policies and supply chain defragmentation as the most commonly cited barrier. It is stated that barriers in different categories are connected to each other, and addressing each can remove several barriers.

The significance of barriers varies across sectors such as the built environment and the construction industry. Hart et al. (2019) examined the barriers and enablers of CE implementation in the built environment, highlighting cultural and financial barriers, as well as supply chain fragmentation, as the most significant, while acknowledging the presence of technical and regulatory barriers. AlJaber et al. (2023) also identified challenges and barriers to CE implementation in the building sector through a systematic review. Among the many barriers identified, the absence of CE regulations, a fragmented supply chain, and high initial investment costs were highlighted as the most significant. At the same time, Munaro and Tavares (2023) mentioned technological and political barriers as the most prominent barriers in literature.

Different research projects have identified different categories as important barrier categories. For example, O'Leary et al. (2024) highlighted that CE implementation can differ between the building and railway sectors because the clients are different. Focusing on a certain sector, like the railway system, and identifying the importance of barriers can be more useful, as it gives a clearer understanding of CE barriers in that domain. O'Leary et al. (2024) investigated the importance of different CE implementation barriers for UK railways and found client leadership as the most important factor. Koohmishi et al. (2025) also listed technological, financial, and regulatory issues as the barriers and potential risks for CE implementation in ballasted railways.

In this study, we aim to understand the current CE practices for the Swedish railway system and identify and evaluate the CE implementation barriers for the Swedish railway system. The methods used in this study consist of a literature review, interviews, and a questionnaire. A literature review was conducted to find the main barriers to CE implementation in the railway system. 24 barriers are classified into six different categories, including "Awareness", "Technology, products, and processes", "Business models & procurement", "Policy and regulation", "Behavior, culture & values", and "Infrastructure". Thereafter, we interviewed CE experts in the railway system and designed a questionnaire to explore and identify the important barriers in the Swedish railway system.

2. CE Practices in the Railway Sector

In recent years, the benefits of CE have been realized in the railway industry as it contributes to resource efficiency, cost savings, waste reduction, and energy efficiency. However, there are limited CE implementations and experience in the railway sector (O'Leary et al. 2024).

CE implementation through UIC members was explored in the REUSE project. Best practices include a rail recycling center, a common European market, reusable inventory list, digitalized platforms, environmental assessment in the design phase, ballast recycling, sleeper repair, and reusing steel components (Meža et al. 2021). Koohmishi et al. (2025) thoroughly reviewed the CE practices in ballasted tracks from 2007 to 2024 using a systematic review.

Waste reduction and waste use as construction materials are two of the most explored objectives of different projects related to CE implementation in the railway infrastructure. Several studies, such as Delgado et al. (2019) and Esmaeili, Yousefian, and Nouri (2019) evaluated the use of steel slag in ballast.

The use of waste rubber in railway infrastructure has been explored in different studies. Chathuri et al. (2023) evaluated and implemented the use of waste rubber additives in the rail track structure. Applications included a ballast mixture with recycled rubber, geogrids made from recycled rubber, and a confining ballast layer with tires. Waste rubber beneath sleepers for the correction of track irregularities has been utilized by Sol-Sánchez et al. (2020). Buddhima et al. (2021) aimed to enhance track stability and reduce ballast degradation while using waste rubber as a layer reinforcement using tires, mats for under-ballast, and sub-ballast material by combining rubber crumbs with coal wash and/or steel furnace slag.

Ballast is a widely used railway material that can be incorporated into a closed-loop system. To enable its reuse, contamination risks must be reduced, an issue addressed by Rak et al. through the development of an environmental risk-based framework (Rak et al. 2022). Based on the ballast condition, different testing methods, ranging from visual inspection and chemical analysis to mechanical testing, should be carried out. The results are then used to classify the risk level, which determines the feasibility of ballast reuse. In some cases, reuse requires cleaning, which can be performed either on-site or at specialized recycling facilities (Meža et al. 2021).

For railway sleepers, circular economy strategies focus on incorporating industrial waste into new production and reusing or repurposing sleepers after their initial service life. Ferdous et al. highlighted composite sleeper production technologies in different countries and categorized them into three groups based on the characteristics of the fibers (Ferdous et al. 2015). However, this type of sleeper production is still at the research and development stages. REUSE project listed the sleeper-related CE practices as reusing sleepers in good condition, repairing, recycling sleeper materials like steel and crushed aggregate, and repurposing after decontaminating for other use like gardening (Meža et al. 2021). CE strategies can be boosted by incorporating specific in the procurement process, as the Swedish Transport Administration implemented in sleeper procurement by adding a term for 18% reduction in CO_2 emissions in comparison to traditional methods without limiting the contractors to specific solutions for projects over 5 million euros (Meža et al. 2021). Sleepers can be reused or repurposed after their initial service life, such as support structures for solar panels, solid walls, roadway surfaces, and wooden bridges (O'Leary et al. 2024; Baranyai et al. 2022).

Other factors, such as inspection activities and related logistics, should also be considered in the CO_2 emissions calculation as assessed by Beg et al. (2025). They assessed the CO_2 emissions of railway maintenance activities and found inspection and logistics to be the most significant part of energy consumption. Reducing fuel consumption is one step towards CE implementation.

When it comes to the railway system, other components like rolling stock, are also incorporated into CE implementation, and the disassembly of locomotives and wagons was evaluated by Phuluwa et al. (2020). They introduced a formula for maximizing the value of bogie components by selecting among reusing, refurbishing, and recycling strategies. The selected strategy depends on its applicability and is also influenced by factors such as defect type and inventory availability.

Digitalized platforms are facilitators in the CE paradigm shift as they can provide useful information such as tracking the history of the assets, condition of the assets, the material composition, and the history of the asset ownership (Meža et al. 2021). The SURPLUS app is an example of digitalization, which is developed for finding and reusing assets in nearby projects (Meža et al. 2021).

3. Research Methodology

Figure 1 illustrates the research methodology. To collect relevant data on the identification of barriers for CE implementation within the Swedish railway system, the study utilizes literature review, expert interviews, and questionnaires as primary methods. A literature review was conducted, and barriers were identified. According to the identified barrier, and to have a more detailed analysis of existing barriers and their importance, a structured questionnaire was distributed and analyzed. Expert interviews were conducted to gain insights into perceptions of CE implementation and associated challenges in the railway sector. The findings from this study aim to support the advancement of CE practices in current railway operation and maintenance, contributing to the transition toward a circular and sustainable transport system within the railway system.

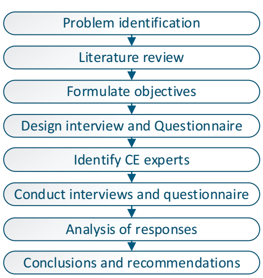

Figure 1- Research methodology

A literature review was conducted to identify the key barriers of CE implementation connected to transport and the built environment. We listed the identified barriers in according to barriers and enablers for CE implementation in the built environment by AlJaber et al. (2023) and the importance of CE implementation barriers for UK railways by O'Leary et al. (2024).

We have adopted the innovation and implementation pillars proposed by Miedzinski et al. (2019) and Jägare, et al. (2024) and categorized the above-mentioned barriers accordingly.

To explore and identify the importance of different implementation barriers in the Swedish railway system, we designed a structured questionnaire study. Thereafter, interviews with experts were conducted, during which we asked eight questions mainly connected with awareness and implementation of CE at the organizational level. The questionnaire was distributed among 25 CE experts, and 17 valid responses were gathered. The distribution of respondents is shown in Figure 2.

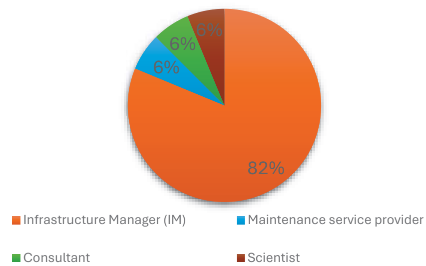

Figure 2- Distribution of respondents to the questionnaire

During the interview, we asked eight key questions covering various aspects of CE in the railway system. Eight experts were interviewed, including railway infrastructure managers, railway contractors, consultants, and researchers. The distribution of the experts is shown in Figure 3.

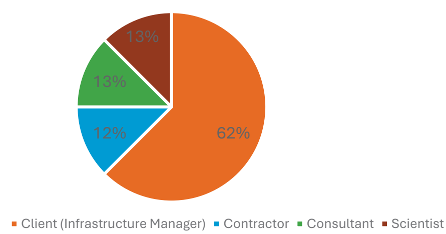

Figure 3- Distribution of experts

The statistical analysis, including mean, standard error, standard deviation, quartiles (Q1, median, Q3), and percentage of unanswered responses, was performed, and the potential barriers were rated accordingly.

4. Results, Analysis and Discussion

As the study comprises interviews and a questionnaire, the results of each are presented in the following sub-sections.

4.1. *Questionnaire Results, Analysis and Discussion*

Respondents rated the importance of each barrier on a 5-point Likert scale (1 = not a barrier, 5 = major barrier). They were allowed to leave it blank if they had no opinion about the importance of the barrier. For each variable, the mean, standard error (SE Mean), standard deviation (StDev), quartiles (Q1, median, Q3), percentage of unanswered responses were calculated. The results of the responses are shown in Table 1.

Table 1- Results of respondents

Variable	Percentage of un-answered	Mean	SE Mean	StDev	Q1	Median	Q3
Insufficient CE knowledge	5.9	3.20	0.28	1.08	2.00	3.00	4.00
Lack of supply chain integration	**0.0**	**3.88**	**0.30**	**1.20**	**3.00**	**4.00**	**5.00**
Insufficient empirical evidence	0.0	3.31	0.31	1.25	2.00	3.50	4.00
Lack of adequate information in railway design, operation and maintenance with regards to CE	5.9	2.87	0.31	1.19	2.00	3.00	4.00
Material Condition at End-of-Life	0.0	3.19	0.29	1.17	2.00	3.00	4.00
Absence of Standardized Circularity Assessment Frameworks	11.8	3.21	0.33	1.25	2.75	3.00	4.00
Complexity of the wide-ranging product and volumes reaching EOL	**11.8**	**3.71**	**0.32**	**1.20**	**3.00**	**4.00**	**5.00**
Insufficient Market Support for Material Reuse	11.8	3.50	0.33	1.23	2.75	4.00	4.25
Market Price Advantage of Virgin Materials	**0.0**	**4.13**	**0.30**	**1.20**	**3.25**	**5.00**	**5.00**
Market Imbalance in Circular Material Flows	5.9	3.67	0.30	1.18	3.00	4.00	5.00
Financial Uncertainty in Circular Construction Investment	5.9	3.53	0.24	0.92	3.00	4.00	4.00
High Initial Investment for Circular Economy Transition	17.6	3.62	0.35	1.26	2.50	4.00	4.50
Lack of an overall policy for the railway system on how to deal with CE	0.0	3.44	0.33	1.32	2.00	4.00	4.75
Insufficient Financial and Motivational Incentives for Circular Economy Adoption	5.9	3.40	0.36	1.40	2.00	4.00	5.00
Insufficient Government Incentives and Regulatory Support for Circular Economy Transition	0.0	3.38	0.32	1.26	2.25	4.00	4.00
Lack of consistent, supportive policies and regulatory framework for CE	11.8	3.64	0.25	0.93	3.00	4.00	4.00
Gaps in Standards, Certification, and Traceability	0.0	3.25	0.28	1.13	3.00	3.50	4.00
Unrealistic belief on CE	11.8	3.21	0.30	1.12	2.75	3.00	4.00
Lack of interest in CE	0.0	2.94	0.32	1.29	2.00	3.00	4.00
Fragmented, uncollaborative, adversarial railway industry	17.6	2.85	0.34	1.21	2.00	3.00	4.00
Lack of a database and information in CE practices	17.6	3.15	0.32	1.14	2.50	3.00	4.00
Storage and Site Limitations	**11.8**	**3.71**	**0.34**	**1.27**	**3.00**	**4.00**	**5.00**
Lack of infrastructure for supporting CE management	5.9	3.47	0.27	1.06	3.00	4.00	4.00
A traditional and disconnected industry following a linear economy approach	5.9	3.53	0.36	1.41	3.00	4.00	5.00

Based on the questionnaire results, some barriers are considered more important than others. The variables highlighted in Table 1 received the highest mean scores, indicating their prominence. However, around 12% of participants did not express an opinion on these variables, and the reported values are based only on those who rated them. This may indicate a need for clarification or reflect sectoral differences and limited experience with CE among experts.

The high scores indicate that the economic competitiveness of virgin materials, logistical challenges, and regulatory inconsistencies are the most commonly perceived issues. Most of the variables had a high response rate, indicating strong participant engagement. However, three barriers, including "fragmented, uncollaborative, adversarial railway industry", "lack of database and information in CE practices", and "high initial investment for circular economy transition" had a 17.6% non-response rate. This could reflect a lack of awareness or understanding among respondents, pointing to areas where clarification may be necessary. "Lack of interest", "Lack of CE information in railway operations", and "Fragmented, adversarial industry" as the lowest-rated CE barriers revealed that cultural barriers are the least important ones.

Although barrier categories may be interconnected, the barriers were categorized based on the literature review. The analysis was conducted using sub-variables linked to each category, enabling the calculation of their average importance. The results are presented in Table 2.

Table 2- Categorical importance of barriers

Category	Average
Business models, investments, and procurement	3.69
Infrastructure	3.47
Policy and regulation	3.42
Technology, products, and processes	3.37
Awareness	3.31
Behavior, culture, and values	3.00

"Business models, investments, and procurement" is the most important category. The related barriers to this category were also highlighted during the interview. The relatively lower average scores for some categories suggest that while awareness and cultural challenges exist, they are not the biggest barriers, but they could cause problems if not addressed.

4.2. *Interview Analysis*

Most experts stated that they do not have a transition towards CE in place as the concept is new in the railway sector, but they will consider a transition toward CE in the future.

Lack of CE standards and codes in CE assessment and implementation is another existing challenge. Approximately 90% of respondents indicated that their organizations do not follow any specific CE standards or codes. Using recently published ISO standards in the absence of specific CE standards was pointed out by one of the experts from an infrastructure manager (IM). The lack of specific standards for storage areas was also highlighted.

25% of the experts did not have information about the current and future CE plans in the railway system, which reflects awareness as a barrier. Strict technical regulations and a conservative, safety-focused industry culture in the current business model act as the main barriers. CE adoption also often depends on individual project managers, while time, cost, and lack of specialized resources make reuse less attractive. CE goals are not clearly defined, project documents rarely include circularity requirements, and the current technical framework (TRVINFRA-00018 2023) only supports limited material reuse, restricting broader application. It has also been mentioned that enabling terms for CE implementation need to be stated in the project documents, which is not the case today.

A key barrier to CE implementation is the cultural belief that it is primarily the responsibility of the maintenance department, particularly since most CE efforts occur during operation and maintenance. During construction, the focus remains on quality and budget, with little attention to circularity KPIs. Additionally, the lack of historical data and incomplete databases limits the ability to assess CE performance across different asset types. Another barrier is the waste management responsibility in construction contracts, which lies with contractors, and without standardized digital reporting. IMs struggle to track waste flow, further hindering effective CE implementation and evaluation.

5. Conclusion

In this study, we gathered information from experts' opinions to explore the CE implementation barriers in the Swedish railway system through interviews and a questionnaire. Some of the main findings of this study are as follows:

- The transition toward CE implementation will be considered in the future, but several barriers slow down the adoption and implementation process.
- In the literature, cultural barriers to CE are listed as the most important barriers; but as a result of the categorization and aggregation of the variables, cultural barriers were rated as the least important barrier category for the Swedish railway system.
- While experts emphasized some barriers during interviews but rated them as the least important ones in the questionnaire; this implies that the importance of barriers can differ based on the context.
- Scoring the importance of CE barriers revealed that all barriers have varying scores (i.e., impact), and the main barriers have scores higher than 2.5. On the other hand, the difference in the scores of different categories is not significant.
- The current business model limits the implementation and integration of CE principles in the Swedish railway system. For example, existing contracts do not provide incentives to adopt CE practices. Multiple stakeholders involved in the design and construction phases primarily focus on meeting technical specifications, often without considering circularity. As a result, the responsibility for CE implementation is left to the maintenance phase.
- The questionnaire revealed that economic competitiveness of virgin materials, logistical challenges, and regulatory inconsistencies are the most highlighted barriers. In contrast, the interview stated that the existing business models were the primary barrier limiting CE implementation in the railway system.
- The implication of this study is that a strategic direction and concerted efforts will be required to promote the implementation of CE by addressing the barriers identified in this article.

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