Faculdade de Engenharia da Universidade do Porto

Social Responsibility in Mechanical Engineering: Solutions for Portugal's Railway Sector

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Resumo

Com a crescente exigência para que o setor da engenharia adopte práticas de responsabilidade social, este princípio tornou-se um ponto de extrema importância. Assim, esta dissertação foca-se no papel da responsabilidade social no setor da engenharia mecânica, centrando-se especificamente em soluções relativas à ferrovia portuguesa. O objetivo principal é propor um modelo de implementação de medidas ligadas à responsabilidade social, no setor ferroviário, ilustrando a sua aplicabilidade através de um caso de estudo onde a análise a vários materiais é realizada.

Para tal, foi realizada uma pesquisa abrangente do estado atual da ferrovia, destacando os seus pontos fortes, pontos fracos, oportunidades e ameaças. A investigação analisa ainda vários aspetos da responsabilidade social, tanto a nível geral como do setor ferroviário, incluindo materiais, práticas de fabrico, normas e diretrizes, e práticas notáveis.

Além disso, e contribuindo para o modelo de implementação, foi efetuado um inquérito para avaliar a perceção e o envolvimento das diferentes partes interessadas no setor da ferrovia, bem como para analisar o potencial de iniciativas do cariz da responsabilidade social também neste setor, obtendo mais de 1000 respostas válidas. Relativamente ao caso de estudo anteriormente referido, este avalia o potencial de optar por materiais sustentáveis para painéis interiores de comboios de passageiros, avaliando as propriedades mecânicas, propriedades acústicas e desempenho geral.

Os resultados do inquérito sugerem que os passageiros estão altamente preocupados, tanto com o estado da expansão da rede ferroviária, como com o preço de viajar neste setor, deixando para trás as apreensões ligadas à sustentabilidade. Esta priorização por parte dos passageiros revela as áreas da ferrovia que necessitam de atenção e reforma, demostrando o caminho que o modelo de implementação deve seguir. Relativamente ao caso de estudo, foi concluído que apesar dos materiais não satisfazerem os requisitos de aplicação à ferrovia, há ainda potencial para alterar os parâmetros de estudo, e por isso obter resultados mais positivos. Porém, ficou evidenciado que a incorporação de materiais sustentáveis e de todos os tipos de práticas centradas no passageiro, pode contribuir significativamente para os objetivos de responsabilidade social do sector ferroviário.

Abstract

With the increasing demand for the engineering sector to employ social responsibility practices, this concept has become an extremely significant concern. Therefore, this dissertation centers on the role of social responsibility in the mechanical engineering field, with a particular emphasis on solutions that apply to the Portuguese railways. It is the primary goal to suggest a model for the implementation of social responsibility initiatives in the railway sector, and to demonstrate its applicability through a case study that involves the analysis of a variety of materials.

To achieve this objective, an in-depth study was conducted into the current state of the sector in question, emphasizing its strengths, vulnerabilities, opportunities, and threats. The study also examines a number of social responsibility-related topics, including materials, manufacturing procedures, norms and guidelines, and noteworthy practices, both generally and specifically in relation to the railroad system.

Additionally, a survey was conducted to evaluate the perception and engagement of different stakeholders in the railway business, as well as to examine the potential for implementation of social responsibility initiatives in this field, thereby contributing to the model. Over 1000 valid responses were obtained. In the preceding case study, the potential of selecting sustainable materials for passenger train interior panels is assessed, including their mechanical, acoustic, and overall performance.

The survey results indicate that passengers are extremely concerned about the condition of the rail network's expansion and the cost of travel in this sector, which has removed pertains regarding sustainability. The railroad's areas that require attention and reform are revealed by the prioritization of passengers, which illustrates the path that the implementation model should follow. In the context of the case study, it was determined that the materials do not satisfy the criteria for railroad application; however, there is still the potential to modify the study parameters and yield more favorable outcomes. It was evident, however, that the railways' social responsibility objectives could be significantly enhanced by the integration of sustainable materials and a variety of passenger-centered practices.

Keywords: Social Responsibility; Sustainability; Railways; Material Testing; Stakeholders

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"Nothing is lost, nothing is created, everything is transformed."

Antoine Lavoisier

Contents

List of Figures

List of Tables

Abbreviations

AM	Additive Manufacturing
APAC	Associação Portuguesa dos Amigos dos Caminhos de Ferro
CCFP	Companhia dos Caminhos de Ferro Portugueses
CFRP	Carbon Fiber Reinforced Polymers
CP	Comboios de Portugal
CSR	Corporate Social Responsibility
DGTT	Direção Geral dos Transportes Terrestres
EoL	End-of-Life
FETT	Fundo Especial dos Transportes Terrestres
FRP	Fiber Reinforced Polymers
FST	Fire, smoke, and toxicity
GP	Green Production
IMT	Instituto da Mobilidade e Transportes
ISO	International Organization for Standardization
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
PC	Polycarbonate
PFN	Plano Nacional Ferroviário
PLA	Polylactide
PRR	Plano de Recuperação e Resiliência
SAW	Simple Additive Weighting
SDG	Sustainable Development Goal
SPSS	Statistical Package for the Social Sciences

Nomenclature

μ	Expected Value
H_0	Null Hypothesis
H_1	Alternative Hypothesis
$\sigma_{\text{specified}}$	Stress Goal
σ_{peak}	Stress at impact peak
α	Sound Absorption Coefficient
V_{sample}	Sample Volume
m_{sample}	Sample Mass
ρ	Density
A_{total}	Total Area
A_{layer}	Layer Area
n	Number of Samples per Cubic Meter
$f_1(F)$	General Function Related to Functional Requirements
$f_2(G)$	General Function Related to Geometric Parameters
$f_3(M)$	General Function Related to Material Properties
S	Sound absorption coefficient
I	Impact Force Handled
C	Cost per Square Meter
W	Weight of a 100mm x 100mm Sample
M_{material}	Material Index

Chapter 1

Introduction

1.1 Background

With the growing pressure of businesses to incorporate environmental, economic, and social factors into their operations, the concept of social responsibility has gained considerable attention in recent years across numerous industries. This shift has engendered a reassessment of conventional methods in the field of mechanical engineering, placing greater significance on ethical decision-making and sustainable development.

On account of a number of compelling factors, the Portuguese railway system is an ideal candidate for the implementation of social responsibility principles. To begin with, the railway system assumes a crucial function in fostering regional progress, linking urban areas and being a fundamental element of the nation's infrastructure. Significant progress towards the societal objectives of accessibility, inclusivity, and equity can be made by the railway industry through the enhancement of its social responsibility.

Furthermore, although generally quieter than alternative modes of transportation like air or road travel, the environmental repercussions of the railway sector are not inconsequential. The railway provides an optimal setting for the implementation of sustainable practices, as endeavors to reduce resource usage and safeguard biodiversity are in close accordance with the domains of social responsibility (social, economic, legal and environmental).

Moreover, the welfare of communities situated along train routes is directly influenced by management of the railway services. The cultivation of trust and the promotion of positive relationships between the railway industry and different communities can be achieved through active participation in development initiatives, attentive engagement with stakeholders, and resolution of their concerns.

With efforts to decarbonize the transportation sector and investments in railway infrastructure, the Portuguese Government has ultimately shown its dedication to responsible transportation solutions (Government of Portugal, 2020b). The railroad industry can leverage this factor to integrate social responsibility into its operations and increase its contribution to sustainable development.

1.2 Motivation

The motivation for this thesis is fundamentally rooted in a conviction regarding the capacity of engineering to bring significant and visible societal changes. Mechanical engineers, in their capacity as agents of progress and transformation, should employ their knowledge in furtherance of more extensive societal goals such as ecological preservation, economic advancement, and social equity.

Furthermore, a critical evaluation of the current state of the Portuguese railway sector, which reveals a convergence of opportunities and obstacles on the path to social responsibility, provides the impetus for this thesis. Although this industry has a notable history of technological advancements and efficient operations, it also faces systemic challenges including outdated infrastructure, regulatory limitations, and deeply ingrained cultural values that prioritize immediate financial gains at the expense of long-term viability. Additionally, a dedication to bridging the gap between theory and practice by translating concepts of social responsibility into concrete implementable approaches serves as another motivation for this thesis.

Additionally, the case study provided in the chapter 4 was motivated by the desire to determine the viability of exploring non-traditional materials with minimal environmental consequences for application in the railway industry. This is a concrete application of the potential that mechanical engineering has in contributing to social welfare and environmental improvement.

1.3 Research Problem

The Portuguese railway system, being essential for transportation and economic progress, encounters a range of complex obstacles that require a re-evaluation of its operational structure. One of the primary obstacles is the necessity to harmonize railway operations with modern benchmarks of social responsibility, which include environmental conservation, economic sustainability, and societal welfare. The current research issue pertains to the effective integration of social responsibility principles into the operations, policies, and decision-making processes of the Portuguese railway sector.

The present issue needs a comprehensive examination of the cultural, operational, and structural dynamics of the railway sector in order to identify leverage points, systemic obstacles, and strategic opportunities that can facilitate the advancement of social responsibility goals. Moreover, this research transcends theoretical investigation, demanding the comprehension of the interplay between institutional, regulatory, and cultural factors that influence the Portuguese railway sector. Through an examination of technological advancements, policy frameworks, and stakeholder dynamics (in this case through a survey), this research endeavors to formulate practical and expandable approaches that effectively enhance performance metrics related to social responsibility.

1.4 Objectives of the Study

The primary aims of this research are to:

- Conduct an examination of the present condition of the Portuguese railway industry, discerning its merits, drawbacks, prospects, and challenges with regard to social responsibility.
- Propose a framework tailored to the unique characteristics and challenges of the railway sector, emphasizing social responsibility across environmental, economic, and social dimensions, and assess the feasibility and potential impacts of its implementation, considering scalability and stakeholder acceptance.
- Construct a case study to illustrate the potential of the implementation of a social responsible initiative, specifically exploring the use of sustainable materials for train interior wall panels, assessing their properties.

1.5 Scope and Significance

This research is situated within the sector of the Portuguese railways, with a principal emphasis on improving social responsibility in its activities. Although the principles and methodologies outlined in this document may have wider implications, the present focus is on the distinct challenges and prospects encountered by the railway services in Portugal.

An aspect that holds importance is the incorporation of social responsibility factors into the realm of manufacturing processes and materials. Through a commitment to ethical sourcing, resource efficiency, and sustainability in material selection and supply chain management, this research endeavors to illustrate how conscientious engineering practices can cause significant change in the face of present-day environmental and social issues.

The research presented in this study holds practical implications for policymakers, academic researchers and railway stakeholders, presenting improvements in decision-making processes, fostering innovation, and facilitating concrete enhancements in the social responsibility performance of the sector, through the provision of actionable insights, evidence-based recommendations, and real-world case studies. Moreover, this research encompasses interdisciplinary collaborations and initiatives for the exchange of knowledge that go beyond conventional academic disciplines.

1.6 Thesis Structure

Four additional chapters comprise this dissertation, following the Introduction.

A comprehensive literature review and an overview of the current state of the art are presented in Chapter 2. Chapter 3, presents the development and examination of a framework specifically designed to enhance social responsibility in the Portuguese railway industry.

In Chapter 4, a Case Study is presented, centering on the potential of replacing current materials with sustainable alternatives. This case study effectively illustrates the practical implementations of social responsibility initiatives within the railway sector.

In the last chapter, concluding remarks are provided, key findings are summarized, and potential directions for future research are outlined. The limitations and objective's satisfaction are also presented.

Chapter 2

Literature Review

The current section of literature review establishes the foundation for a study within the field of social responsibility, specifically focusing on its application across mechanical engineering and the railway sector in Portugal. Various aspects of social responsibility will be investigated, including its conceptualization, its application in materials and manufacturing processes, as well as how it complies with global practices. Additionally, an extensive examination of Portugal's railway scenario, along with an evaluation of patterns and obstacles enables a profound comprehension of the potential for development in this sector.

2.1 Social Responsibility in Mechanical Engineering

2.1.1 Defining Social Responsibility

The concept of social responsibility has experienced a significant transformation, reflecting substantial shifts in society expectations and ethical frameworks (Abdelhalim and Eldin, 2019). Davis (1967) was crucial to this development, as it established the foundation for comprehending social responsibility as a complex concept that includes law and power as principal dimensions.

This work also questioned the dominant belief that companies had the main purpose of maximizing profits, instead appealing for a more sophisticated approach that recognizes the connections between corporate operations and the welfare of society. According to this study, ethical obligations require enterprises to conduct themselves with honesty, impartiality, and a dedication to preserving human rights. Simultaneously, businesses are obligated by legal responsibilities to be responsive to all rules and regulations, guaranteeing conformity with societal norms and standards.

Feldberg (1974) enhances this discussion by defining social responsibility as a crucial and necessary action for organizations. He underscores the imperative for businesses to take an active role in anticipating and addressing societal demands, rather than merely responding to regulatory restrictions or public criticism. Schwartz and Carroll (2003) built upon this matter by developing the Three-Domain Approach to corporate social responsibility (CSR). This method highlights the dependence of economic, legal, and ethical duties, suggesting that businesses must care for all of these, in order to have long-lasting prosperity. In addition to these three obligations, Schwartz and Carroll (2003) also proposed a concept of optional responsibilities ie. voluntary initiatives aimed at resolving social needs and promoting sustainable development. Figure 2.1 illustrates the concept in discussion.

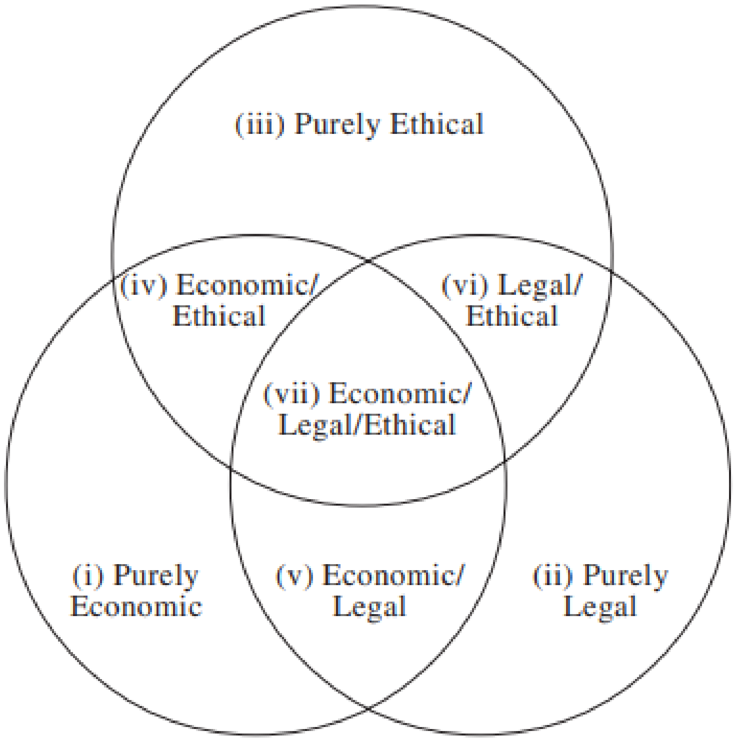


Figure 2.1: The Three-Domain Model of Corporate Social Responsibility (Schwartz and Carroll, 2003).

In addition, a newer study emphasizes the increasing significance of integrating environmental factors into social responsibility initiatives. During the era of Sustainable Development Goals (SDGs), companies are facing both challenges and opportunities that require them to integrate environmental concerns into their plans. The Environmental dimension covers obligations to integrate sustainability into all the activities of companies, for example, the designing, the manufacturing, the supplying and the distribution of products (Lu et al., 2018).

As the discussion surrounding social responsibility grows stronger, mechanical engineers are increasingly expected to make active contributions towards the development of positive transformations. Such viewpoints provide a foundation for re-evaluating the selection of materials and manufacturing techniques, which will be discussed in the following subsection.

2.1.2 Social Responsibility in Materials and Manufacturing

Social responsibility is a fundamental idea in contemporary engineering approaches, covering aspects like environmental accountability, social equality, and financial viability (Bielefeldt, 2018).

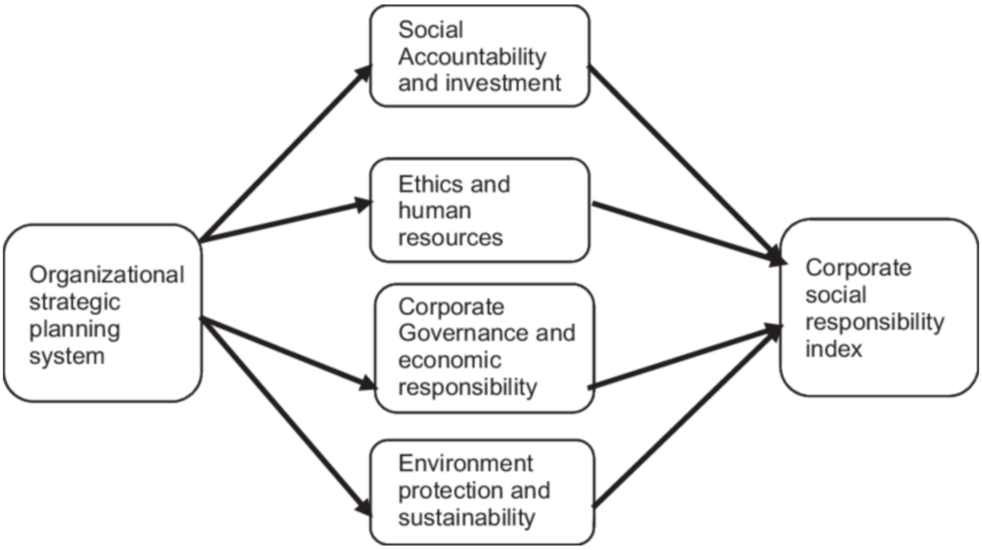


Figure 2.2: Recent Model of Corporate Social Responsibility (Khan and Szegedi, 2020).

Ethical issues are essential in engineering, going beyond personal choices to include broader societal implications and obligations. Herkert (2005) explores the idea of macro-ethics, which underscores the significance of analyzing ethical matters at the systemic level within engineering procedures. Engineers may address complex ethical challenges and support sustainable development goals by embracing a macro-ethical viewpoint.

Within the macro-ethical perspective, engineering codes of ethics promote environmental conservation as a professional responsibility. The American Society of Mechanical Engineers (2012) provides ethical guidelines and regulations for engineers. This code emphasizes the significance of maintaining ethical standards in engineering work, which includes factors such as sustainability and environmental responsibility. Bielefeldt (2018) delves deeper into the notion of professional social responsibility in engineering, highlighting the engineers' responsibility in advancing sustainable development and asserting that sustainability encompasses present circumstances and the well-being of future generations.

The concept of green production (GP) comes from the ideology of sustainable development. It is a crucial element of sustainable manufacturing that emphasizes energy conservation, reduced consumption, and pollution minimization (Guo et al., 2015). GP is the systematic application of a environmental strategy to improve effectiveness and reduce hazards to individuals and the environment in operations, goods, and services, as defined by the United Nations' Environmental Program. GP aims to expand manufacturer accountability to products and the environment by promoting ecological advantages and sustainable growth. Corporations must tackle numerous obstacles and execute precise strategies to achieve GP. Implementing it, involves utilizing resources efficiently, preventing material loss, and enhancing product designs, equipment, and production processes (Tsai et al., 2014).

Another concept for sustainable engineering practices is material circularity, focusing on enhancing the active stock of materials, encouraging reuse, refurbishment, and recycling, and decreasing the amount of material disposed of in landfills (Torres Marques et al., 2023). This technique entails implementing superior material technologies, design methodologies, and extending the longevity of items. This contributes to environmental regulations, zero pollution, transparency, traceability, and climate impact. In addition to material circularity, the use of additive manufacturing offers prospects for sustainable production by allowing items to be developed in an environmentally conscious way. Rapid prototyping, product industrialization, and large-scale production can decrease waste and encourage material circularity (Torres Marques et al., 2023).

Social responsibility in materials and manufacturing involves balancing and integrating objectives such as achieving harmony with nature, efficient resource use, reducing CO2 emissions, and protecting the planet, while also considering global economic growth (Torres Marques et al., 2023). This strategy integrates several social elements and is in line with the Sustainable Development Goals (SDGs). The next section will focus on the function of standards and guidelines related to social responsibility in engineering processes. Standards in this context are essential frameworks that direct engineering efforts towards ethical practices, highlighting the need of environmentally sustainable, socially fair, and commercially feasible solutions.

2.1.3 Standards and Guidelines

Addressing global concerns and promoting sustainable development need the incorporation of Sustainable Development Goals (SDGs) into engineering projects (Torres Marques et al., 2023). The United Nations (UN) established 17 SDGs as part of its 2030 Agenda, addressing various topics such as poverty eradication and environmental sustainability (Gueorguiev and Kostadinova, 2021). These goals (present in Figure 2.3) serve as a framework for worldwide action, highlighting the importance of cooperation and creativity to achieve a more sustainable future.

Within mechanical engineering, SDGs are especially relevant to materials and manufacturing processes, as it is necessary to articulate the different aspects to achieve sustainable development (Torres Marques et al., 2023). SDG 9, "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" and SDG 12, "Ensure sustainable consumption and production patterns" emphasize the significance of sustainable industry and production cautions (Gueorguiev and Kostadinova, 2021).

Standardization efforts can help include SDGs into engineering procedures. International standards, including those created by the International Organization for Standardization (ISO), offer direction on how to adopt sustainable practices and achieve particular sustainability objectives. ISO standards like ISO 14001 and ISO 26000 provide frameworks to synchronize their operations with Sustainable Development Goals (SDGs) (Stanislavska et al., 2010). These standards aid in maintaining uniformity, clarity, and responsibility in sustainability efforts, allowing firms to monitor advancements and showcase their dedication to sustainable development (Sitnikov and Bocean, 2012).

Figure 2.3: Sustainable Development Goals (United Nations, 2023).

Specifically, ISO 14001 outlines criteria for developing, executing, sustaining, and enhancing environmental management systems (Gueorguiev and Kostadinova, 2021). This standard helps organizations in controlling their environmental effects and conforming with applicable legislation, consequently supporting Sustainable Development Goals concerning environmental sustainability (International Organization for Standardization, 2015) . Furthermore, this standard highlights the significance of systematic approaches in environmental management, such as identifying environmental factors, compliance with responsibility, and operational controls. Certification under ISO 14001 allows firms to show their dedication to environmental oversight, enhancing their reputation and competitiveness in the market (De Colle et al., 2014).

ISO 26000, on the other hand, provides only recommendations on incorporating social responsibility into business operations, covering topics like human rights, labor practices, and environmental involvement (International Organization for Standardization, 2010a). This standard is a crucial step in advancing the concepts of CSR and sustainability in different sectors, such as engineering (Hahn, 2012). ISO 26000 provides guidelines on social responsibility that focuses on improving organizational performance and societal effect, rather than seeking certification like traditional management system standards. It encompasses many aspects of social responsibility, including human rights, labor practices, environmental stewardship, and community engagement. As Hahn (2012) expressed, ISO 26000 states that companies can actively promote the achievement of the SDGs regarding environmental justice and social equity by cultivating a panorama characterized by ethical behavior, openness, and responsibility.

Although standardization offers advantages, companies may face obstacles when trying to apply sustainable practices efficiently. Among the problems mentioned are: conceptual deficiency, additional expenses related to certification and absence of enforcement mechanisms (De Colle et al., 2014). Addressing these obstacles requires collaboration across stakeholders to increase awareness, offer assistance, and promote adoption. As Gueorguiev and Kostadinova (2021) state, organizations may improve their sustainability performance and help achieve the Sustainable Development Goals by overcoming these obstacles.

2.1.4 Remarkable Sustainable Practices

Sustainable manufacturing has become a central focus in many companies, as stated before. Multiple strategies have been implemented, with numerous efforts made to enhance the sustainability of products and processes (Norani et al., 2014). This section will explore some valuable examples of practices within this matter.

Norani et al. (2014) presented a case study on sustainable manufacturing processes in the context of a Malaysian firm referred as Company XY. This company produces composite parts and sub-assemblies for the aircraft sector, working with major industry players such as *Boeing* and *Hexcel* as well as local partners. The company was recognized as the Best Kept Industry by the Kedah State (Malaysia) in 2006, making it a significant organization for this Literature Review. Despite the organization's request for staying anonymous, critical information regarding their procedures was exposed.

Company XY's sustainable manufacturing is based on four main sections: Responsive Product Strategy, Lean Practices, Supply Chain Restructuring, and Sustainable Material and Design. The company demonstrates sustainable manufacturing practices through the use of quality improvement tools like Six Sigma and Design of Experiment, also prioritizing Environmental, Health, and Safety (EHS) and maintaining accreditation under standards such as ISO 14001. Additionally, the organization prioritizes the creation of precise Bills of Materials (BoMs) to manage expenses and minimize inefficiencies in production procedures.

The aspect identified as key-reason of success is the use of Lean manufacturing concepts, which enhance efficiency, minimize waste, and improve resource utilization. Lean manufacturing approaches also lead to energy savings by decreasing space usage, transportation needs, and product re-work. These activities are in line with broader sustainability objectives by reducing consumption of materials. Besides all this, the corporation also actively monitors water consumption to minimize environmental effects and operating expenses. Strategies involve evaluating water usage efficiency, reducing pollutants in wastewater, and investigating options for water reuse and recycling. These methods offer various advantages, including improved product quality, increased customer satisfaction, resource preservation, and cost savings. Initiatives such as punctual delivery, exploitation of recycled carbon fiber, and development of environmentally friendly materials strengthen the company's strategic success and competitive edge in the aerospace sector.

Another remarkable case study has been developed, this time set in New Zealand. Seidel et al. (2006) examines *CML Ltd*, a leading New Zealand furniture producer known as the largest panel furniture maker in Australasia. *CML Ltd* has adopted a continuous improvement strategy to boost its manufacturing performance and then identified sustainability as a new way to strengthen its competitiveness. For this second part, the company requested assistance from the Department of Mechanical Engineering at the University of Auckland to investigate some sustainable means of production. Initially, the task included to uncover strategic hazards or opportunities by examining pertinent local and international environmental laws and regulations. It also aimed to assess *CML Ltd*'s waste management strategies to ensure compliance with laws and regulations, including collecting data on trash produced in production operations. Overall, the project aims to start a Product Stewardship initiative to find options for sustainable management.

The first stage of the project focused on establishing the groundwork for incorporating sustainability within the company's management procedures. This entailed assessing *CML Ltd*'s present circumstances, identifying variables in its business environment and markets that could be influenced by or benefit from sustainable production, and identifying tools, methodologies, support programs, and exemplary practices to aid advancement. For this, a comprehensive SWOT analysis was performed as well as a Stakeholder analysis, highlighting governmental institutions and environmental groups that are crucial for the sustainability project. The importance of environmental labeling in communicating the sustainability of *CML Ltd*'s products to consumers was also studied. Three Eco-labels were found to be promising for *CML Ltd*'s needs after thorough research: Environmental Choice New Zealand label, Forest Stewardship certification, and Enviro-Mark®. Following these procedures, new sub-goals were created to develop a life cycle inventory of furniture production, pinpoint chances for enhancing sustainability in manufacturing procedures, and include sustainability into *CML Ltd*'s management procedures.

The inclusion of these case studies in this section was crucial for a variety of reasons. To begin with, it presents an actual illustration of how sustainable manufacturing methods can be implemented within the framework of a medium to large-scale enterprise, thereby highlighting the opportunities that such businesses might face. The case study of *CML Ltd* underscores the importance of integrating sustainability into management operations in a strategic manner. It offers businesses an in-depth plan for enhancing their environmental performance while maintaining their competitive edge. These insights can be applied to a variety of additional industries.

2.2 Rail Transportation in Portugal

2.2.1 Historical Perspective of Portugal Railways

During the 1850s, when the initial Portuguese railway lines were established, numerous nations had already developed their railway networks and had initiated the exportation of their knowledge and skills in railway manufacturing and construction. Foreign investors, primarily from Great Britain and France, identified a chance to further grow their businesses in Portugal.

Initially, British investors played a significant role in constructing key railway lines in Portugal, such as *Linha do Norte, Linha de Leste*, and *Linha do Sul*. The *Linha do Norte* provided a link between the coastal cities of Lisbon, Coimbra, Aveiro, and Porto, running through the country in a north-south direction. The *Linha de Leste* was the inaugural international railway designed to connect the Seaport of Lisbon with the rest of Europe, specifically intended for transporting freight. However, the conflicting goals between British investors and the Portuguese government caused difficulties that led to the cancellation of these concession deals. Investors were reluctant to embrace the concept of a rail route linking Portugal and the rest of Europe as it threatened the established maritime economic monopoly (Vieira, 1988).

British participation in the railways was marked by controversies that delayed the construction progress. Because of that, the Portuguese railway's primary structure was constructed between 1859 and 1883 by French railway firms, with financial help from private investors like *Crédit Financier* and other British stakeholders. These French businesses had previously developed the Spanish railway network and linked it to France. Merging the Spanish and Portuguese railway networks with the French network seemed to be an attractive financial opportunity for those companies. Portuguese private investment in railways finally appeared and chose to focus on secondary lines in the northern region due to the proximity of most Portuguese industries (Vieira, 1983).

Figure 2.4: Matosinhos Old Train Station (Comboios de Portugal Document Centre and Historical Archive, 2024).

The goal of the government was never to manage the construction of a profit-oriented railway network. State-run railway construction and management occurred inadvertently in cases where no private proposals had been submitted, rather than deliberately managing the allocation of the most lucrative lines. This also demonstrates the aim to establish infrastructure in disadvantaged and remote regions, providing a chance for rural advancement and mineral resource utilization. Although external pressures first drove railway expansion in Portugal, it eventually led to the state taking ownership of specific railway lines (Pinheiro, 1979). The state-owned railway network established, ceased operations in 1927 due to a new railway control approach. In March of that year, the state-owned corporation was leased to the *Companhia dos Caminhos de Ferro Portugueses* (CCFP), a Portuguese railway business under French control. Furthermore, the railway infrastructure was finally regulated and classified by decree 13829 on June 17, 1927 (Direcção Geral de Caminhos de Ferro, 1929).

Isidoro et al. (2018) notes that the decreed project plan includes a greater number of lines for the central and northern regions of the country compared to the southern region. Coastal locations have more projected lines than inner territory. Despite that, in the twentieth century, every Portuguese city was linked to a network originating from Lisbon and Porto. Migratory patterns increased significantly following the introduction of railways, originating from both domestic and foreign sources. The lack of a passenger railway network in the country's interior indicates that the existing lines in these regions were specifically constructed for international transportation links (Sousa et al., 2011). Moreover, each plan's intention to sustain a significant number of foreign routes underscores the railway's importance in accessing global markets. While railways facilitated the growth of exports, they also provided a new avenue for imports.

Several projected lines of the decreed plan of 1927 were not constructed due to the emergence of a dictatorship in 1933, which hindered private investment (Pinheiro, 1979). Governmental initiatives decreased the dominance of railways as a transportation method, allowing for the promotion of the automobile sector in the national market. Decree 22379, issued in 1933, was the initial step that prohibited the construction of new railway lines (Ministério das Obras Públicas e Comunicações, 1933). During the dictatorship period, just a few railway tracks owned by the state were operational. This measures had an immediate impact on transportation services and their users.

Law no.2008, from September 7th, 1945, marked a significant change in railway laws by merging all private railway firms into the single concession of the previous mentioned CCFP. This corporation underwent a comprehensive restructure, transferring administration and funding to Portuguese operators (Isidoro et al., 2018). During the years 1933 to 1945, the number of private railway businesses declined from eight to two. While the railway industry faced closures, road transportation companies did not encounter similar limitations. Decree 38247, established in 1951, granted the automotive sector expanded market access by creating the *Direção Geral de Transportes Terrestres* (DGTT) and implementing the *Fundo Especial de Transportes Terrestes* (FETT). Both road and rail transit were now managed by a unified agency, and the newly established fund was divided between both forms of travel.

Portugal remained unaffected by the economic crisis that Europe experienced during the Second World War due to its non-involvement in the conflict and lack of destruction compared to other European nations. Nevertheless, the government participated in the European Economic Recovery Program, which sought to incorporate American funding into the reconstruction of Europe after the war. Between 1953 and 1964, the railway company obtained funding for various projects including electrification, renovation of certain railway lines, upgrading of signaling and telecommunications systems, and modernization of workshops for new electrical and diesel-electric equipment (Martins et al., 1996).

In 1955, both Portugal and Spain adopted the 1668mm Iberian Gauge as their standard. Portugal implemented this standard in order to preserve its trade connections, however, it failed to avoid the isolation of the Iberian Peninsula, leading to political and economic complications (Ferreira, 2012).

By the 1970s, the automobile industry had flourished in Portugal, initiating a competition between road and rail transportation. The decline in railway users prompt authorities to consider shutting down underutilized lines. Despite the proposal of a modernization plan by the CCFP, the subsequent nationalization of the railway company in 1974, renaming it *Comboios de Portugal* (CP), worsened its financial situation, making the portuguese railways unable to compete with road transport (Martins, 1996).

Between 1976 and 2011, approximately one-third of Portuguese rail lines were either partially or completely deactivated, as seen in Table 2.1. This move primarily affected regions already served by road transportation, contributing to demographic decline, especially in the economically weaker southern inland cities. The gradual shift from rail to road transport, coupled with the deactivation of international lines, further reduced the railway's competitiveness (Sousa et al., 2011).

Table 2.1: Railway Lines Dismantled Since 1969 (Isidoro et al., 2018).

Railway Lines Dismantlement	**Year**	**Length (km)**
Linha de Guimarães	1989	56
Linha do Minho	1990	16
Linha Porto–Póvoa–Famalicão	2002	57
Linha do Douro	1998	28
Ramal de Alfândega	1989	4
Linha do Tua	1992	130
Linha do Corgo	2011	96
Linha do Tâmega	2011	55
Linha do Vouga	1990	79
Linha da Lousã	2010	30
Linha do Dão	1989	49
Linha de Leste	2011	141
Ramal de Cáceres	2011	72
Vendas Novas-Setil	2011	70
Ramal de Montemor	1987	13
Ramal do Montijo	1987	12
Linha do Sueste	1990	42
Linha de Portalegre	1990	20

Ramal do Seixal	1969	4
Ramal de Sines	1990	48
Linha de Évora	2011	102
Linha do Guadiana	1990	41
Linha de Mora	1987	60
Ramal de Aljustrel	1976	11
Total of deactivated lines	1236	

The decision to dismantle 1236 km of railroad was implemented through various restructuring programs, including the *Programa de Encerramento de Linhas de Tráfego Reduzido (1972), Plano de Modernização e Conversão da CP (1988), and Plano Estratégico de Transportes (2011)*. Most closures were due to the lack of modernization and the increasing budget required for maintenance, aggravated by the big economic crisis that ruled between 2010 and 2014. Despite the decline in traditional rail services, suburban lines serving Lisbon and Porto's satellite cities remained profitable, highlighting the disparity in investment between different railway segments (Isidoro et al., 2018).

A few years later, Portugal's rail network was brought back as a top priority as part of the *Ferrovia 2020* Program, implemented in 2016. This program involved investing almost 2 billion euros to enhance more than 1,000 km of railroads (Infraestruturas de Portugal, 2021). This program was supposed to be finished by December 2020, but has experienced substantial delays. By the deadline, just three out of the eighteen planned projects were completed, comprising just 5 % of the intended kilometers of railway line to be constructed or improved (Cipriano, 2020). As a result, the country has approximately the same length of railway tracks in 2021 as it did in 1893 (Cipriano, 2021). Despite difficulties, there has been a significant increase in the number of passenger-kilometers across the studied period, with the exception of 2020 and 2021 due to pandemic-related restrictions. In 2019, CP reported 4,436 million passenger-kilometers, a notable rise from the 3,625 million passenger-kilometers in 2015 (Comboios de Portugal, 2019).

In 2022, a new national railway plan emerged in a hard environment, supported by funds from *Plano Nacional de Investimentos* 2030 and *Plano de Renovação e Resiliência Português*, with the goal of rejuvenating the country's railway industry. The main aim of this plan is to notably boost the percentage of rail transport used, aiming to grow it from 4.6% to 20% in passenger travel and from 13% to 40% in freight transport, all by 2050. The initiative aims to create service connections in 28 major areas throughout Portugal, including all district capitals, and to prepare for high-speed connections with Spain. This approach involves building a new high-speed network, creating new railway lines, and improving existing ones, while also increasing the capacity and efficiency of the current infrastructure. The strategy also focuses on enhancing connections to major airports and promoting inter-modality with different transportation modes to establish a well-integrated and effective network (Ministério das Infraestruturas e Habitação, 2022).

Despite this optimistic panorama, *Ferrovia 2020* construction is still in progress, resulting in over twenty million liters of fuel burned that might have been avoided if the project had been finished on schedule (Cipriano et al., 2024).

2.2.2 Materials and Manufacturing Practices in Rail Transport

Advancements in materials and manufacturing practices have played a crucial role in the development of the railways, with several materials coming in hand for several applications within the sector. During the 18th century, cast iron was introduced for rails, initially as plates on wood tracks. Additionally, rails started to be curved to aid in vehicle steering. Besides mentioning the above, Perez-Unzueta (1992) also states that in 1789, W. Jessop created cast wheels designed to run on iron rails, which had the initial form of the rounded rail head on a flange arrangement similar to present rails.

Since the introduction of steam locomotives in 1803, it was discovered that the current cast iron rails were insufficient due to their tendency to fracture easily, highlighting the importance of enhancing the quality of the rails. Henry Bessemer invented a steel-making technique in 1856, which was later enhanced by R. Mushet to produce ingots suitable for forging and rolling. In the following 20 years, rail transverse profiles were quickly evolved and eventually adopted the overall shape used globally today (Perez-Unzueta, 1992).

The railway system uses the rail as a beam support for vehicles' weight on spaced sleepers. The wheel and rail are designed to allow steering around bends with minimal frictional resistance to rolling movement. Accordingly to Garnham and Davis (2009), the system remains mainly unlubricated to ensure sufficient driving and braking traction. The rail head material experiences compressive rolling and sliding forces due to minimal contact area with the wheel, leading to wear and eventual rolling contact fatigue on both surfaces.

The rail's resistance to wear and fatigue is defined by its chemical composition, steel manufacturing method, and hot forming technique, given a maximum contact stress and vector of maximum deviation. Garnham and Davis (2009) explains that, nowadays, rails have predominantly been made from low-alloy, carbon-manganese steel with medium to near-eutectoid carbon levels on most railway systems worldwide, mainly due to the affordability of these types of steels. The typical composition consists of pearlite, which is a lamellar structure of carbide and ferrite, with differing amounts of pro-eutectoid ferrite at the previous austenite grain boundaries. In higher carbon grades, the presence of pro-eutectoid ferrite is minimal and in some newer grades, absent.

Currently, in Japan, Europe, and various other nations, the majority of rail steel blooms are manufactured via continuous casting. This ensures a high level of uniformity in the product, with the size and distribution of non-metallic inclusions being influenced by the cross-sectional area of the continuously cast bloom and the subsequent rolling reduction needed to achieve the specified rail profile (Boulanger, 2003).

To improve the life-cycle of railway tracks in severe environments, enhancements have been made by reducing or removing pro-eutectoid ferrite through the use of higher carbon grades and refining the pearlitic structure. This has been achieved by controlled cooling, alloying with elements like chromium, and refining the grain size of prior austenite. Various steel structures have been studied, but advancements in bainitic structures, namely low-carbon and alloyed, have been thoroughly investigated. While they do not provide any advantages in wear resistance in typical settings, they significantly aid in weld joining Garnham and Davis (2009).

The main driving forces for introducing new materials in the rail sector are the demand for a lightweight design and reducing manufacturing costs. Different efforts have been made to integrate composites into this industry (Larrode et al., 1995). Compared to the aerospace, automotive, and marine sectors, the railway industry has been seen as falling behind in using lightweight materials in its constructions. Cost, fire performance, and maintenance concerns in the railway environment have obstructed the broad deployment of composites. Composite design can save manufacturing expenses by minimizing the quantity of components, assembly procedures, and assembly duration, as seen from a life-cycle costing viewpoint (Larrode et al., 1995).

Fiber reinforced polymer (FRP) is a type of composites that fulfills these goals. This materials offers exceptional properties and capability of creating complex, three-dimensional profiles ideal for rail vehicle design. Rail vehicle design is typically separated into major modules such as the intermediate end, body side, roof, cab front, under frame and bogies. Composites for semi-structural interior applications tend to utilise glass fibres and low-cost grades of thermoset polymers. Only for some projects, such as high-speed trains, where weight reduction is a necessity, are carbon fibre and higher-performance resins, such as epoxies used (Mistry et al., 2020).

The fire, smoke, and toxicity (FST) regulations (British Standards Institution, 2013) in the rail industry impose significant limitations on material selection and the adoption of new materials. Regarding fibers, glass fibers are predominantly utilized in rail applications because of their favorable mechanical qualities and cost-effectiveness when compared to carbon and aramid fibers. The lightweight glass fiber composite constructions are limited in structural performance due to the absence of fiber alignment in the current formats. Regarding resins, thermosetting resins including unsaturated polyester, vinyl-ester, and epoxy are typically chosen for rail applications. Nevertheless, a drawback of these resins is their FST performance. The unsaturated version of polyester quickly burns, producing smoke and harmful fumes. To address this issue, fillers and additives are utilized to enhance fire resistance. Another option are phenolic resins, that are naturally fire-resistant and produce little amounts of smoke and harmful fumes (Kelly and Zweben, 1999).

Regarding the composition of the rail car, it is usually constructed using lightweight, rigid panels or sandwich panel constructions composed of two FRP skins enclosing a lightweight core. Sandwich panel structures utilize polymer foams, balsa, and honeycomb cores for cab ends, body sides, and floors. Balsa, a lightweight and eco-friendly wood, is frequently selected for its affordability, as mentioned by (Kelly and Zweben, 1999). Sandwich panel structures with honeycomb cores are now the dominant method for constructing rail vehicle hulls and interior paneling. These have strong strength and exhibit good impact and energy absorption qualities. Sandwich-paneled rail cars such as Schindler Wagon's Revvivo, Munico, and Neitec vehicles. The Korean Tilting

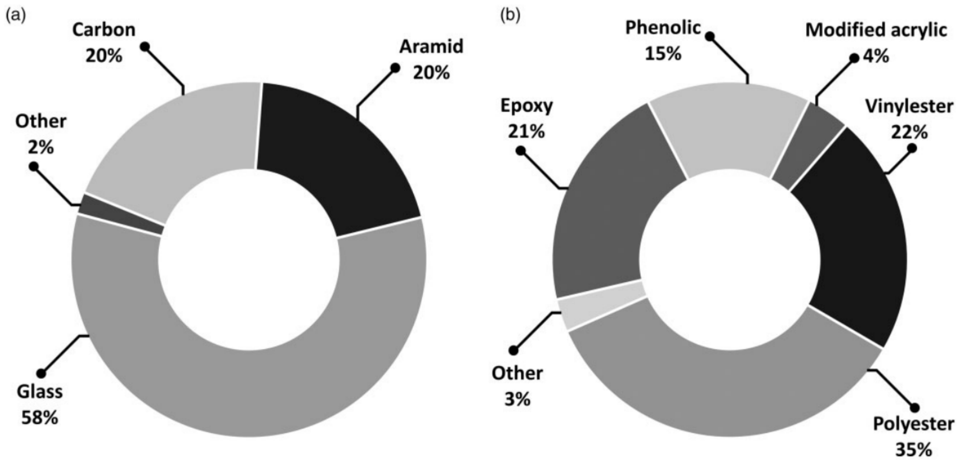


Figure 2.5: Summary of (a) Reinforcement Fibres and (b) Matrix Resins Used, in terms of volume, in the Manufacture of Composite Components for Rail Vehicle Applications (Robinson, 2016).

Train eXpress and Bombardier's C20 are other examples (Knutton, 2003).

Composite manufacturing techniques in the rail industry are influenced by the need for simplicity and cost-effectiveness. Most rail components are produced in quantities ranging from 50 to 5000 pieces per year, requiring the use of manual lay-up and spray lay-up procedures due to the low volume production. These methods are straightforward but require a significant amount of labor. Vacuum infusion is suitable for larger parts and low volume production, while resin transfer molding is often utilized for medium volume production. Matched die molding of sheet molding compound has been utilized for producing seat shells due to the cost-effectiveness of high-volume production despite the expensive tooling costs (Kelly and Zweben, 1999).

2.2.3 Sustainability Panorama of the Portuguese Railway Sector

The *Plano Ferroviário Nacional* (PFN) from 2022 is Portugal's recent strategic plan for developing railway infrastructure, crucial for improving transportation connections and promoting economic growth as briefly explained in the end of the section 2.2.1. The PFN went through rigorous environmental assessment procedures, since they are required by Decree-Law n. 232/2007 and Decree-Law n. 58/2011 . This section analyzes the environmental report that followed those procedures titled *Avaliação Ambiental Estratégica do Plano Ferroviário Nacional*, focusing on its insights and recommendations (Laboratório Nacional de Engenharia Civil, 2023).

One integral component of this environmental report, is the Strategic Reference Framework (SRF). It assists in evaluating the PFN's interaction with relevant international and national strategic instruments, as well as potential conflicts, synergies, and coordination. To facilitate a more targeted environmental evaluation, when a European strategic instrument is equivalent to a national strategic instrument on the same subject, only the national strategic instrument is taken into account (e.g., as a consequence of the transposition of a European Directive).

Some global instruments that are relevant for the PNF are stated in the Table 2.2, involving international initiatives provided by United Nations (2015), UNESCO (1972), European Commission (2020); the European Union (2020), European Parliament and Council of the European Union (2021). On the national dimension, the responsibles is the Government of Portugal (2001). Regarding local matters, the Instituto da Conservação da Natureza e das Florestas (2020) and Government of Portugal (2020a).

Bellow, in Table 2.2, the analysis of the relationship between each of the instruments refereed and the dimensions of the PFN is presented. In this analysis of coordination, the following relationships were considered:

- Strong coordination (XX) – when there is a significant and direct strategic coherence between the instrument and the functional axes of the PFN;
- Weak coordination (X) – when there is a less significant or indirect strategic coherence between the instrument and the functional axes of the PFN;
- No relationship (-) – when there is no relationship between the instrument and the functional axes of the PFN.

Table 2.2: Analysis of the axes of the PFN (Laboratório Nacional de Engenharia Civil, 2023).

	Freight Transport	**Passenger Transport**	**Urban Passenger Transport**	**Tourism and Heritage**
Paris Climate Agreement	XX	XX	XX	-
Convention Concerning the Protection of the World Cultural and Natural Heritage	-	-	-	X
SDGs	XX	XX	XX	-
Agenda for a socially fair transition towards clean, competitive and connected mobility for all	X	X	X	-
Territorial Agenda 2030	X	XX	XX	X
Urban Agenda for the European Union	-	-	XX	-
EU's 2050 long-term strategy	XX	XX	XX	-
Sustainable and Smart Mobility Strategy	XX	XX	XX	X
European Climate Law	XX	XX	XX	-
White Paper on Transport	XX	XX	X	-

Table 2.2: (Continued) Analysis of the axes of the PFN.

	Freight Transport	**Passenger Transport**	**Urban Passenger Transport**	**Tourism and Heritage**
Connecting Europe Facility	XX	XX	-	-
Fit for 55 Climate Package	X	X	X	-
European Green Deal	XX	XX	XX	X
EU regulations and guidelines on rail transport	XX	XX	-	-
European regulations and guidelines on noise and public health	XX	XX	XX	-
Common Cross-Border Development Strategy	X	XX	-	X
Portugal 2030	XX	XX	XX	XX
Portuguese Climate Framework Act	XX	XX	XX	XX
Portuguese Law on Cultural Heritage	-	-	-	X
National Plan for Hydrogen	XX	XX	XX	-
Natura 2000 Network Sector Plan	-	-	-	-
National Action Program to Combat Desertification	-	-	-	-
Inland Development Program	XX	XX	-	X
Road-map to Carbon Neutrality	XX	XX	XX	X
Programs for Protected Areas	-	-	-	-
Programs for Territorial Planning	XX	XX	XX	XX

This analysis shows that the PFN has an effective alignment of its three functional axes with international, European, and national policies concerning environmental and climate issues. The functional axis of Freight Transport has a strong alignment with socio-economic development tools and governmental programs like the Portugal 2030 Strategy and the Interior Development Program.

The operations in the Long and Medium Range Passenger Transport axis shows good synchronization with most of the previously described instruments. It can also be seen the coordination of the Metropolitan and Local Passenger Transport axis with smart and sustainable mobility instruments, along with considerations related to territorial planning and socio-economic development. The actions under the Tourism, Heritage, and Railway Culture functional axis are directly coordinated with some national instruments related to territorial planning and indirectly coordinated with other considered instruments.

Having discussed the relationship between the PFN and the various policies, it is now appropriate to assess the plan's implications across various elements of social responsibility.

The initiatives outlined in the PFN are designed to improve the competitiveness of railway freight transport and strengthen the appeal of collective passenger rail transit for medium and long-distance journeys as well as local commuting. The rise in the modal share of railway transport for both freight and passengers, along with the decrease in individual transport, and the gradual electrification of the railway network, will significantly help in lowering greenhouse gas emissions and pollutants from the transportation sector. The PFN deployment may reduce noise sources but can also have negative consequences due to the prevalence of overnight freight transport on trains.

Implementing the PFN could enhance the railway network's ability to adapt to climate change, thus boosting the resilience of the transport system. Although, it may also introduce dangers related to floods or the likelihood of fires and accidents during the transportation of hazardous materials. When discussing biodiversity and nature conservation, it is noted that besides the disruption caused by water lines, the construction of barriers in habitats intersected by new routes could have adverse effects.

Regarding territorial and social cohesion, the PFN can improve it by ensuring a fairer distribution of railway transit at the regional level and facilitating the promotion of local resources and history. The PFN has led to greater integration of the railway mode in national and international logistics chains, resulting in improved productivity and accessibility for export activities. Bellow, Table 2.3 is shown to illustrate the impact panorama.

The environmental assessment led to recommendations from the authors to address gaps in the PFN and ensure that the plan's execution meets environmental and sustainable development objectives in accordance with European and national policies. The investigation showed that in addition to the listed favorable outcomes, there are some hazards that must be avoided and reduced. It is suggested that PFN projects evaluate their impact on strategic objectives and environmental effects by estimating the anticipated environmental benefits and quantifying their environmental impact using relevant indicators such as tons of CO2 equivalent avoided per year. Furthermore, it is proposed to efficiently prioritize projects in order to optimize environmental and social advantages. Alongside all of this, collaboration among relevant organizations should also be encouraged.

Another suggestion is that platforms for intelligent management of urban mobility and freight traffic should incorporate features focused on decarbonization, inter-modality, and integrated risk management to enhance the resilience of the railway transportation system and its adaptation to climate change. Citizens and stakeholders, including companies and industries, should learn about the risks and vulnerabilities of the transportation system in different areas and understand the

Table 2.3: Synthesis of the Environmental Effects Assessment (Laboratório Nacional de Engenharia Civil, 2023).

Critical decision factors	Evaluation factors	Distance to goals	Evolution Trends with PFN
Climate change and decarbonization	Decarbonization	Close	+
	Energetic Transition	Close	+
	freight transport logistics	Distant	+
	Green multi-modality in passenger transport	Distant	+
Resilience to natural and technological risks	Adaptability to Climate Change	Distant	+
	Articulation with policies to prevent accidents involving dangerous substances	Close	0
Natural capital, environment, landscape, and cultural heritage	Water Resources	Distant	-
	Air Quality	Close	+
	Noise and vibrations	Distant	+
	Biodiversity and Nature Conservation	Distant	0
	Cultural Heritage	Close	0
Territorial cohesion, mobility, and accessibility	Population dynamics, land use and urbanization	Distant	+
	Sustainable Mobility	Far Away	+
	Accessibility and equal access to services	Far Away	+
Competitiveness and innovation	Industry Competitiveness and Research Development	Distant	+
	Interoperability of rail transport and international connectivity	Far Away	+

available transportation options. This will help them be better prepared and respond effectively to extreme events.

To protect public health from noise exposure, it is advised to regularly monitor environmental noise levels using data from Municipal Noise Maps and Strategic Noise Maps and to include the evaluation of low-frequency vibrations (16 Hz - 250 Hz) and structural noise radiation in environmental impact assessments for railway infrastructure (underground and surface) within the PFN scope. This is important for buildings with sensitive use near the infrastructure.

Given the high construction level of the PFN, it is recommended that the assessment of the impact of the Railway Network on water bodies, both in terms of quantity and quality, as well as in terms of hydro-morphological changes and ecosystems, be highly considered in the environmental impact study of the projects. The construction of new transportation infrastructure should always be preceded, by an environmental impact assessment, considering sustainability criteria. Considering the interaction between territorial infrastructure and land use dynamics, possible reductions in transportation costs (e.g., in interurban travel through electric mobility) may lead to "rebound effects" with the consequent transformation of land use (urbanization), alongside negative effects on territorial planning associated with potential unregulated dynamics in the real estate market (acquisition of second homes). Thus, these effects should be properly preempted in territorial management instruments, and other policy measures should be applied.

Regarding cultural heritage, it is recommended to adapt the impact assessment to the scale of buildings or tangible and intangible assets, taking into account the guidelines of the International Council on Monuments and Sites on Heritage Impact Assessments, in accordance with the methodology outlined (International Council on Monuments and Sites, 2022), as well as the measures proposed by UNESCO World Heritage Centre (1998).

Concerning the promotion of territorial cohesion, mobility, and accessibility, it is recommended that initiatives provide improvement on territorial and social cohesion by focusing on understanding the socio-economic conditions and mobility/accessibility demands of the population, especially in urban regions, and by taking into account the possibility of job creation and economic expansion that may arise from enhanced accessibility, in line with regional development objectives. National, inter-municipal, and municipal statistics and planning organizations should consistently gather mobility and accessibility data, and spatially distribute them throughout urban and non-urban areas.

It is important to focus on collecting specific indicators for distinct purposes, including the percentage of the population with access to flexible or communal transportation and the average journey time on collective transportation for various activities. Projects in cities such as Lisbon and Porto should be in line with sustainability and carbon neutrality goals. Hence, it is crucial to take into account the cumulative environmental impacts, particularly those associated with land use planning. Assessing the environmental consequences of combining projects from different sub-sectors is crucial.

The expansion of industrial regions and upgrades to the railway network will benefit rural areas by expanding options for integrating and marketing products in broader markets. This involves advocating for tourism activities associated with natural and cultural assets. Enhancing and repairing lacking linkages in border regions can improve permeability between territories on both sides of the boundary. This promotes international service usage, expands service options for the public, improves service efficiency, and boosts territorial competitiveness. Investments in transportation and mobility need to align with the urbanization paradigm in both metropolitan areas and small to medium-sized cities.

In summary, the PFN aids in the resolution of existing obstacles in the realm of transportation and mobility, taking into account societal and environmental concerns on a national and international scale. This will be accomplished by enhancing freight and passenger transportation's capacity, service quality, and operational efficiency. However, some conflicts with sustainability were identified, particularly concerning noise, water resources, biodiversity, and its conservation.

Chapter 3

Social Responsibility in the Portuguese Railways: Proposed Framework

The proposed framework is built upon a thorough survey and a complete analysis of articles and publications related to the subject of research. Through this process, essential principles and strategies pertinent to fostering social responsibility within railways have been collected.

Moreover, the incorporation of perspectives obtained from a comprehensive customer survey, which received a remarkable value of 1066 responses, provides this framework with valuable insights.

A number of suggestions that are not explicitly associated with the environment will be discussed in consideration of the fact that social responsibility encompasses a vast array of extremely diverse topics, namely related to several dimensions that involve the passenger.

3.1 Scope and Approach

The framework's scope extends to the detailed assessment and improvement of Social Responsibility practices in Portuguese railways.

In addition, the framework will incorporate suggestions derived from a systematic analysis and insights gathered from the customer survey. In addition, a legal framework, risk assessment and a materialization of the insights gathered from the survey responses will be incorporated. The aforementioned elements will guarantee the thorough justification for the potential execution of social responsibility endeavors within the Portuguese railways, thereby cultivating an environment that promotes conscientious business conduct and sustainable progress. The collection of data is also made through a benchmark of social responsible business practices within foreign railways.

The visual approach of the framework is provided below, Figure 3.1.

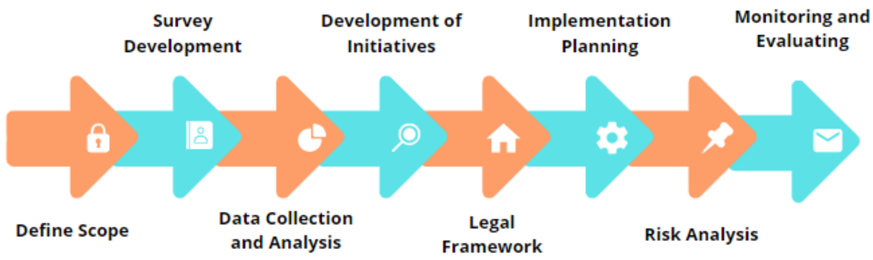


Figure 3.1: Steps of this Framework.

3.2 Current Scenario

CP Comboios de Portugal is an essential component of Portugal's transportation sector, offering indispensable rail services throughout the country. When examining CP's current situation, it is possible to identify several important aspects that reveal the company's approach to social responsibility.

Promoting the significance of ethical conduct, openness, and engagement of all stakeholders, CP exhibits a robust commitment to social responsibility. At the core of their principles is a commitment to serving individuals, guaranteeing secure working conditions, safeguarding the environment, advocating for human rights, and nurturing social integration.

CP's website is a crucial platform for stakeholders to access information about the company's operations, initiatives, and commitments. Nevertheless, it is worth noting that the website is not updated frequently. The absence of regular updates may prevent stakeholders' ability to access timely information, such as updates on social responsibility initiatives and sustainability reports, as well as information about routes and international trains.

These sustainability reports are an essential aspect of CP's transparency initiatives as they provide stakeholders with a thorough assessment of the company's performance across different domains, such as environmental responsibility, social influence, and corporate governance. Nevertheless, there is a significant lack of recent sustainability reports extending beyond the year 2020. This discrepancy gives rise to inquiries concerning the company's commitment to transparency and accountability, as stakeholders may be lacking up-to-date information on CP's advancements and difficulties in meeting its social responsibility objectives.

Although there are no recent reports, the 2020 sustainability report showcases CP's operational difficulties, which encompass a significant 40% reduction in passenger transport, a 45% decline in traffic revenue, and a negative net result of €95.4 million, indicating an 85% decline compared to the previous year (Comboios de Portugal, 2020).

Despite this situation, CP places a strong emphasis on sustainability, which is a core principle that guides its actions. This principle is based on three main pillars: protecting the environment, ensuring social fairness, and maintaining economic viability. These pillars function as the foundation for CP's strategic decision-making and operational practices accordingly to the 2020 sustainability report.

For that, CP has been prioritizing the welfare of their workforce, which includes providing comprehensive health insurance coverage and adhering to collective labour union agreements, even in the face of intermittent strikes. Environmental initiatives encompass the reduction of diesel consumption, CO2 emissions, and the attainment of a waste valorization rate of 76%.

CP's societal impact is significant, demonstrated by the transportation of 86.9 million passengers and the operation of 404 thousand trains, all of this during the pandemic. Regarding corporate actions, such as the merger with EMEF to bring maintenance operations in-house, clearly show their dedication to improving service quality and operational efficiency.

This report also identifies stakeholders, which include customers, suppliers, NGOs, and educational institutions. Their sustainability agenda encompasses multiple facets, such as environmental conservation, employee welfare, customer satisfaction, and operational effectiveness, in line with the United Nations' Sustainable Development Goals (SDGs).

In the future (post 2020), CP is dedicated to enhancing its environmental performance, ensuring safety, improving accessibility, promoting railway culture, and upholding ethical standards. CP's core values prioritize continuous improvement, which involves adapting to changing sustainability goals and adopting industry best practices.

3.3 Stakeholder Analysis: Survey

The stakeholder analysis survey is an essential part of the Social Responsibility Strategic Plan for Portuguese Railways. Its purpose is to promote a thorough comprehension of some stakeholder viewpoints, preferences, and experiences regarding railway services. The survey aims to provide information that will be used to make decisions and create strategies based on evidence. Functioning as a critical instrument within the wider framework, this survey has been carefully designed to methodically gather data that will contribute to the formulation of practical suggestions intended to improve the Portuguese railway system.

Inspired by the main gaps found in CP's reports, the following research questions were developed (Table 3.1). Associated with the research questions, are the hypotheses formulated for the present investigation. In addition to the themes addressed in the research questions, other themes were explored for quantitative studies, namely addressing customer perspective and feelings that influence their loyalty to the railways.

Table 3.1: Research Questions and Their Hypothesis.

Investigation Question	Hypothesis
Q1: To what extent is there a disparity between generations in the frequency of railway use?	H1: The minority of respondents who frequently use the railway as main transport are Baby-Boomers and from Gen-X.
Q2: How conscious are the respondents about railways' promotional activities?	H2: There is a lack of awareness amongst respondents.
Q3: To what extent does the respondents believe that reliable rail services contribute to territorial cohesion and connectivity in Portugal?	H3: The respondents believe that reliable rail services contribute to territorial cohesion and connectivity in Portugal.
Q4: To what extent does the population believe that having railway infrastructure in all district capitals contributes to promote economic development and social inclusion?	H4: The respondents believe that having railway infrastructure in all district capitals contributes to promote economic development and social inclusion.
Q5: Is there a connection between passengers' wage and the use of railways?	H5: There is a connection between the passenger's wage and railways' usage.

3.3.1 Methodology

3.3.1.1 Rationale for Selecting Survey Methodology

The main instrument used for data collection was a standardized questionnaire. The decision to use survey methodology as the principal approach for gathering data was influenced by a number of crucial factors. To begin with, surveys provide a streamlined approach to collecting information from a broad and varied sample of constituents that are geographically dispersed. In light of the extensive nature of the research, surveys were considered the most pragmatic methodology to guarantee the acquisition of comprehensive and honest data.

Moreover, surveys offer a methodical structure for gathering standardized responses to predetermined inquiries, thereby enabling the systematic examination and comparison of results. This facilitated the collection of consistent and comparable insights, consequently bolstering the dependability and accuracy of the study's findings.

In addition, surveys provide respondents with a certain level of anonymity, which may foster forthright and truthful responses, especially regarding delicate or controversial topics. The provision of anonymity creates a secure setting in which stakeholders are able to openly share their viewpoints and opinions, thereby enhancing the comprehensiveness and depth of the gathered data.

3.3.1.2 Survey Design

The survey instrument was carefully crafted to correspond with the study's aims and research inquiries, guaranteeing its ability to comprehensively encompass the varied viewpoints and experiences of stakeholders pertaining to Portuguese railway services. The survey incorporated a blend of closed-ended and open-ended inquiries, facilitating the gathering of both quantitative and qualitative data.

In order to collect structured responses pertaining to predetermined subjects, including the satisfaction levels, preferences, and perceptions of stakeholders concerning railway services, closed-ended questions were employed. The purpose of these inquiries was to obtain precise data that could be subjected to quantitative analysis, thereby yielding valuable insights regarding trends, patterns, and correlations present in the data.

Conversely, open-ended inquiries granted stakeholders the chance to articulate their viewpoints, recommendations, and apprehensions using their own language. The qualitative data provided a more comprehensive comprehension of the issues at hand by shedding light on the experiences of stakeholders, thereby enhancing the realness of survey results.

The sampling strategy was designed to guarantee that a wide range of stakeholder groups were adequately represented, including passengers and other pertinent actors such as members of APAC *(Associacão Portuguesa dos Amigos dos Caminhos de Ferro)*. Insights from those that do not use railways are also significant, since it is crucial to study the reasons behind their decision to not utilize the service.

Regarding strategy, the research primarily utilized convenience sampling [1], in which individuals were enlisted via diverse channels (social media platforms, email invitations, and targeted outreach to pertinent organizations).

Furthermore, every effort was made to ensure that the survey's structure could be modified to suit the diverse profiles of the participants. The participants were divided into sections according to their residence status - separate sets of inquiries were designed for individuals residing in Portugal and those residing abroad. As a point of reference, those living outside of Portugal were able to share their strongest preferences and criticisms regarding their country's railroads, while individuals living in Portugal were able to express themselves from the experience of whether they use the train services and why. Moreover, participants were further classified according to their utilisation of railway services.

3.3.1.3 Analytical Approach

The survey was conducted electronically through Google Forms, providing respondents with the flexibility to finish the questionnaire at their own discretion. Multiple channels were utilized to distribute the survey: email invitations, social media posts, and targeted outreach to pertinent organizations.

[1] Convenience sampling is a research approach that involves selecting participants based on their accessibility or availability to the researcher. Researchers choose volunteers who are conveniently accessible or readily available, rather than picking individuals from a group at random. This approach is frequently selected in situations where there are limitations such as restricted time, finances, or challenges in reaching the intended group. Although convenience sampling is a time-efficient and cost-effective method, it can lead to biases as the chosen participants may not correctly represent the total population.

The participants were furnished with explicit guidelines regarding the survey's accessibility and completion, alongside details regarding the study's objectives and protocols for safeguarding the collected data. With the assistance of personalized outreach, reminders, and incentives, an effort was made to maximize response rates among key stakeholders.

In order to examine the survey findings, a comprehensive strategy was utilized, incorporating both quantitative and qualitative methodologies. The analysis was performed using the Statistical Package for the Social Sciences (SPSS) for hypothesis testing, and Excel for generating graphs, conducting descriptive statistics, and conducting initial qualitative analysis.

Regarding the software SPSS, the T-Test tool was used to evaluate significant differences in survey responses based on demographic variables or other categorical factors. Furthermore, the One Sample Binomial Test tool was used for ascertain if the proportion of respondents who agree or disagree with specific statements significantly deviates from a hypothesized value.

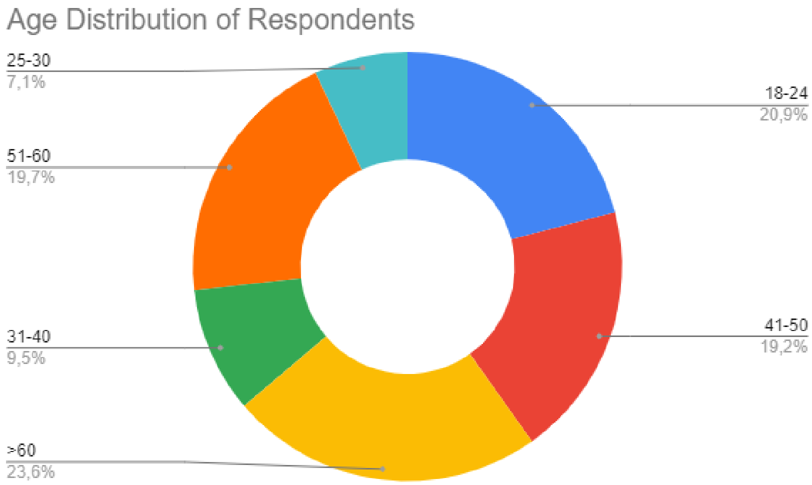
The open-ended survey responses and qualitative data were analyzed using Microsoft Excel. This analysis entails the classification and encoding of responses to discern recurring themes, patterns, and insights. This analysis provides additional contextual information to complement the quantitative findings.

3.3.2 Results

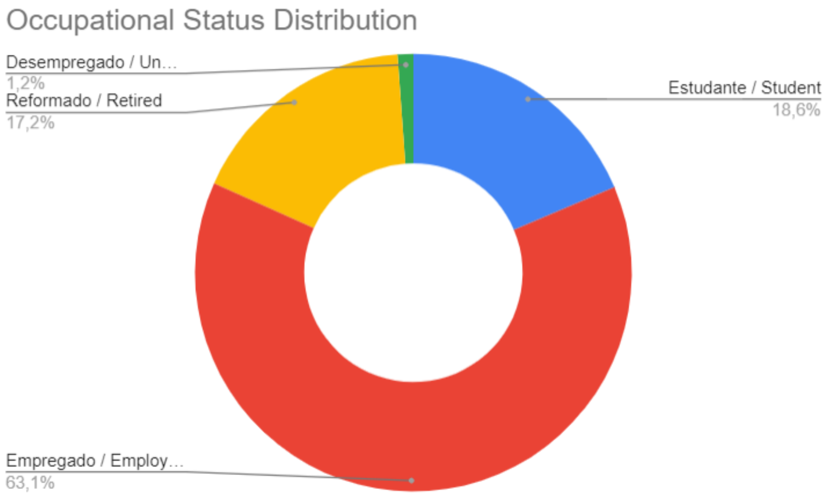
The questionnaire was available for responses over a span of two weeks and garnered a total of 1,066 respondents, encompassing both Portuguese and foreign participants.

3.3.2.1 Demographic Profile

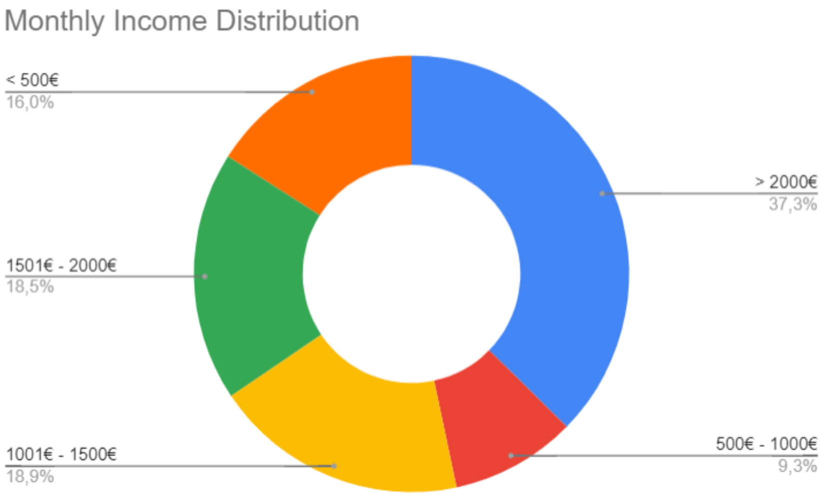
The initial portion of the survey, which includes questions about age, education, occupational status, and wage, serves the purpose of not only addressing research connections but also providing a characterization of the population under analysis. It can be inferred that the age distribution among respondents is fairly even, and the most common occupational status is employment. Regarding wage earnings, a big part of the respondents earn more than 2000€ which may be related to the convenience sampling factor explained in section 3.3.1.2. Each of these conclusions is illustrated in the subsequent graphs.



(a) Age Distribution Between Respondents



(b) Occupational Status Distribution Between Respondents



(c) Wage's Earnings Distribution Between Respondents

Figure 3.2: Various distributions among respondents

3.3.2.2 Hypothesis Testing and Association Between Variables

To address the research questions, the hypotheses outlined in Table 3.1 were proposed. In order to achieve this objective, hypothesis tests and tests of association between variables were conducted using the T-test and Spearman's correlation test. The choice to use Spearman's test was based on being less stringent than Pearson's test. In addition, 95% confidence intervals were utilized to supplement the analysis.

Each hypothesis in Table 3.1 was associated with two defined hypotheses: H0, representing the null hypothesis, and H1, representing the alternative hypothesis. Thus, the null hypothesis can either be statistically rejected or not.

- **First Research Question: Q1**

  Regarding the first research question, the hypothesis (H1) was formulated as "Baby-Boomers and individuals from Gen-X who frequently utilize the railway as main transport constitute a minority of respondents." A non-parametric test was conducted, supplemented by a binomial test to verify the proportion. Additionally, two distinct groups were established: group "1" encompassing individuals aged 40 and below, and group "3" including individuals above the age of 40. It is important to recognize that in this situation, a majority does not simply refer to a result that is above 50 per cent, as it is necessary to consider the margins of error. The value of 54% is thus utilized, indicating a significant enough proportion to be deemed a majority.

  SPSS defines the alternative hypothesis in non-parametric tests as being less than the specified proportion value (in this case 0.54). To determine if the minority belongs to Gen-X and previous generations [2], the proportion must be less than 54 percent. Accordingly, the following is the definition of the expected value (μ), which is the long-run average result of a random variable based on its various possibilities and their corresponding probabilities:

$$H_0 : \mu = 0.54 \tag{3.1}$$

$$H_1 : \mu < 0.54 \tag{3.2}$$

  Figure 3.3 demonstrates a statistically significant result with a p-value[3] of 0.005, indicating a rejection of the null hypothesis at a significance level of less than 5%. Furthermore, a

[2]The generations preceding Generation X (born approximately 1965-1980) include the following:

- The Silent Generation (born approximately 1928-1945)
- Baby Boomers (born approximately 1946-1964)

[3]If the p-value is X, the null hypothesis has a X% chance of being true.

binomial analysis was conducted, providing a clear description of the proportion within each group. The ratio of each group is displayed, affirming the previous inference. Thus, it is feasible to reject the null hypothesis (H0) and infer that the proportion of Gen-X and previous generations is below 54%.

Binomial Test

		Category	N	Observed Prop.	Test Prop.	Exact Sig. (1-tailed)
Generationgap	Group 1	<= 2	64	.65	.54	.021
	Group 2	> 2	35	.35		
	Total		99	1.00		

Nonparametric Tests

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.^{a,b}	Decision
1	The categories defined by Generationgap = 1.00 and 3.00 occur with probabilities .500 and .500.	One-Sample Binomial Test	.005	Reject the null hypothesis.

a. The significance level is .050.

b. Asymptotic significance is displayed.

Figure 3.3: Non-parametric Test Results (Q1).

- **Second Research Question: Q2**

In order to evaluate the second research question, the hypothesis (H2) "There is a lack of awareness amongst respondents" was formulated and examined using a T-test. This was assessed by a survey question regarding the promotions and special initiatives of the Portuguese railway.

The responses were transformed utilizing a Likert scale into numerical values ranging from 1 to 5. Answers 1 ("I am not aware") and 5 ("I am very aware") define the state of being knowledgeable about recent promotional activities concerning railway services. Subsequently, the following hypotheses were formulated, with H0 representing the null hypothesis and H1 denoting the alternative hypothesis. Once more, it is important to note that, SPSS, in non-parametric tests, defines the alternative hypothesis as lower than the value established for the proportion, in this case, 3. Once again the following is the definition of the expected value (μ), which is the long-run average result of a random variable based on its various possibilities and their corresponding probabilities:

$$H_0 : \mu \geq 3 \tag{3.3}$$

$$H_1 : \mu < 3 \tag{3.4}$$

The subsequent phase involved utilizing the SPSS software to conduct a T-Test, which ascertained whether the null hypothesis was rejected or not. A one-tailed right test was conducted, using a 95% confidence interval and a test statistic of 3.

As depicted in the Figure 3.4, the p-value was significantly below 0.05. Based on the provided data, it is feasible to refute the null hypothesis, thereby confirming H2 from Table 3.1.

T-Test

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
awareness	896	1.9275	.94915	.03171

One-Sample Test

	Test Value = 3						
			Significance			95% Confidence Interval of the Difference	
	t	df	One-Sided p	Two-Sided p	Mean Difference	Lower	Upper
awareness	-33.825	895	<.001	<.001	-1.07254	-1.1348	-1.0103

Figure 3.4: T-test Results for Campaigns Awareness.

- **Third Research Question: Q3**

In order to evaluate the third research question, the hypothesis (H3) "The respondents believe that reliable rail services contribute to territorial cohesion and connectivity in Portugal" was formulated and examined using again a T-test.

The responses were, once more, transformed utilizing a Likert scale into numerical values ranging from 1 to 5. Answers 1 ("I don't believe") and 5 ("I strongly believe") define the amount of belief in the contribution of reliable railway services to territorial cohesion and connectivity in Portugal. Subsequently, the following hypotheses were formulated, yet again with H0 representing the null hypothesis and H1 denoting the alternative hypothesis.

$$H_0 : \mu \geq 3 \tag{3.5}$$

$$H_1 : \mu < 3 \tag{3.6}$$

The subsequent phase involved utilizing the SPSS software to conduct a T-Test, which ascertained whether the null hypothesis was rejected or not. As depicted in the Figure 3.5 below, the p-value was significantly lower than 0.05. Based on the provided data, it is feasible to refute the null hypothesis, thereby confirming H3 from Table 3.1.

T-Test

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
cohesion	1007	4.3416	.84039	.02648

One-Sample Test

	Test Value = 3						
			Significance			95% Confidence Interval of the Difference	
	t	df	One-Sided p	Two-Sided p	Mean Difference	Lower	Upper
cohesion	50.660	1006	<.001	<.001	1.34161	1.2896	1.3936

Figure 3.5: T-test Results for the Belief in the Contribution of Railway Services to Territorial Cohesion.

- **Fourth Research Question: Q4**

In order to evaluate the fourth research question, the hypothesis (H4) "The respondents believe that having railway infrastructure in all district capitals contributes to promote economic development and social inclusion" was formulated and examined using for the last time, a T-test.

The methodology was the same as stated before in Q2 and Q3. Answers 1 ("I don't believe") and 5 ("I strongly believe") define the amount of belief in the idea that having railway infrastructure in all district capitals contributes to promote economic development and social inclusion.

$$H_0 : \mu \geq 3 \quad (3.7)$$

$$H_1 : \mu < 3 \quad (3.8)$$

The subsequent phase followed the same patterns as before, so based on the provided data, it is feasible to refute the null hypothesis, thereby confirming H4 in Table 3.1.

T-Test

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Importance	1007	4.5919	.66975	.02111

One-Sample Test

	Test Value = 3						
	t	df	Significance One-Sided p	Significance Two-Sided p	Mean Difference	95% Confidence Interval of the Difference Lower	95% Confidence Interval of the Difference Upper
Importance	75.424	1006	<.001	<.001	1.59186	1.5504	1.6333

Figure 3.6: T-test Results for the Belief in the Idea that Having Railway Infrastructure in All District Capitals is Positive.

- **Fifth Research Question: Q5**

Finally, the hypothesis (H5) that "a correlation exists between the wage of passengers and the utilization of railways" is examined. A Spearman correlation test was conducted in this instance to determine whether or not these variables are correlated or dependent. Consequently, the null hypothesis means that "Variables are independent"(H0) and the alternative hypothesis is "The variables are dependent" (H1).

Observing Figure 3.7, one can discern that the correlation coefficient is set to 1, indicating the presence of the correlation. Moreover, its p-value is significantly below 0.001, which is considerably less than 5%. Therefore, an association between the variables can be confirmed, and the null hypothesis is rejected.

To facilitate a more comprehensive examination, a Whiskers Box graph was constructed, illustrating that an increase in salary corresponds to a decrease in the frequency with which a passenger uses the railroad (figure 3.8).

Correlações

			Rendimento mensal / Monthly Income:	Frequência de uso dos comboios / Frequency of railway use:
rô de Spearman	Rendimento mensal / Monthly Income:	Coeficiente de Correlação	1,000	-,163**
		Sig. (2 extremidades)	.	<,001
		N	895	895
	Frequência de uso dos comboios / Frequency of railway use:	Coeficiente de Correlação	-,163**	1,000
		Sig. (2 extremidades)	<,001	.
		N	895	895

**. A correlação é significativa no nível 0,01 (2 extremidades).

Figure 3.7: Results for Spearman Correlation Test.

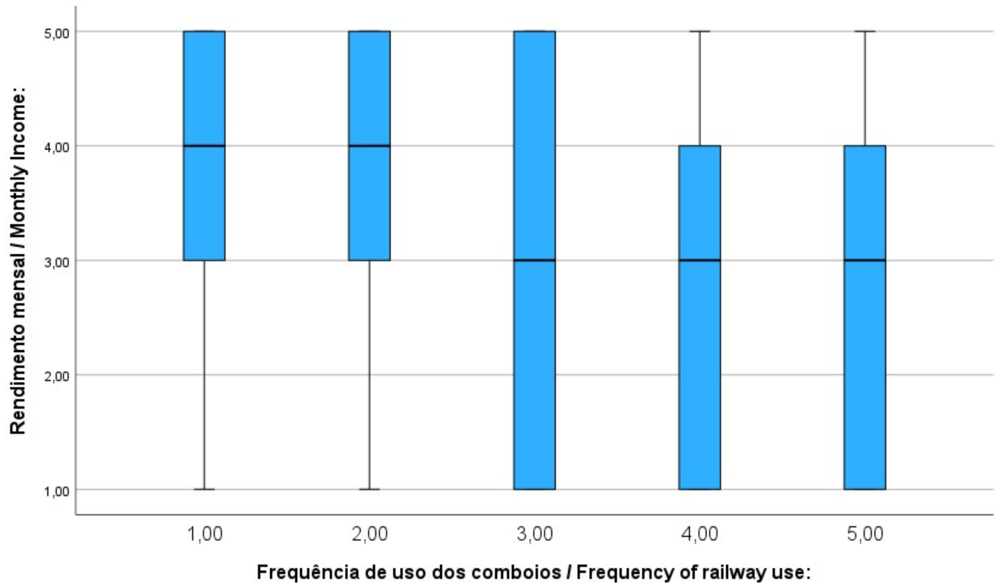


Figure 3.8: Whiskers Box Graph Illustrating that an Increase in Salary Corresponds to a Decrease in the Frequency of Railroad's Usage.

Table 3.2: Confirmation Status of Each Hypothesis.

Hypothesis	Statistical Confirmation
H1: The minority of respondents who frequently use the railway are Baby-Boomers and from Gen-X.	Confirmed
H2: There is a lack of awareness amongst respondents.	Confirmed
H3: The respondents believe that reliable rail services contribute to territorial cohesion and connectivity in Portugal.	Confirmed
H4: The respondents believe that having railway infrastructure in all district capitals contributes to promote economic development and social inclusion.	Confirmed
H5: There is a connection between the passenger's wage and railways' usage.	Confirmed

3.3.2.3 Qualitative Analysis

Qualitative insights were acquired via structured survey questions and open-ended survey responses. The participants were requested to contribute with recommendations aimed at enhancing the railway services in Portugal. They were given the option of providing both predetermined options and written ideas.

Using Microsoft Excel, the analysis was performed. The responses were categorized and encoded in the beginning in order to identify recurring themes, patterns, and insights.

In order simplify the procedure, all feedback proposing any form of Scheduling enhancement was categorized under the overarching theme of "Improving Punctuality" In a similar fashion, proposals pertaining to the enlargement of the railway network to encompass a greater number of destinations were classified as "Network Expansion" whereas notions concerning the provision of inexpensive train tickets and journeys were classified as "Affordability Initiatives".

Insights into the priorities, preferences, and concerns of respondents with respect to railway services in Portugal were derived from the analysis of open-ended survey responses. These concerns were as follows:

- The options that received the highest number of votes (both exceeding 700 answers) concerned the expansion of the railway network and the reduction of ticket prices. A considerable proportion of the participants underscored the importance of expanding the railway system to encompass a wider array of destinations. This indicates that there is a significant need for enhanced connectivity and accessibility throughout various regions of Portugal.
- Numerous respondents also emphasized the significance of reducing the cost of train travel. Provision of discounts and a reduction in ticket prices were among the recommendations put forth in an effort to appeal to a wider spectrum of passengers and enhance overall satisfaction.
- Reliability emerged as another popular choice among respondents. A majority of respondents opt for using cars and buses instead of trains for a significant portion of their trips due to their inability to exercise control over departure and arrival times, which is caused by delays associated with strikes or rail maintenance activities.
- A significant number of passengers continue to have negative associations with the railways' services due to past experiences.
- Additional proposals advocate for the integration of trains with other modes of transportation, such as improving the accessibility of parking facilities or implementing shuttles that link stations to nearby notable locations. A unique proposal was made to incorporate a "ferry" service into the train system, allowing cars to be transported as freight cars alongside the passenger cars.
- It was discovered that the extent of dedication to the environment had a relatively minor impact on voting behavior, in contrast to ticket prices or network expansion. This suggests that while this sector of social responsibility remains a substantial global issue, it may not be the primary concern of the majority of current railway users in Portugal, despite the fact that a "green image" can still be advantageous.
- The length of the railway, punctuality, and comfort are cited by international respondents from successful railway nations like Germany and Italy as the primary factors contributing to their railway's success.

Displayed below in Figure 3.9 are the top-rated choices for enhancing the attractiveness of the railway. It is important to mention that this question included the possibility for multiple answers meaning that the values are not added together, and one participant may prioritize many aspects of the railroad.

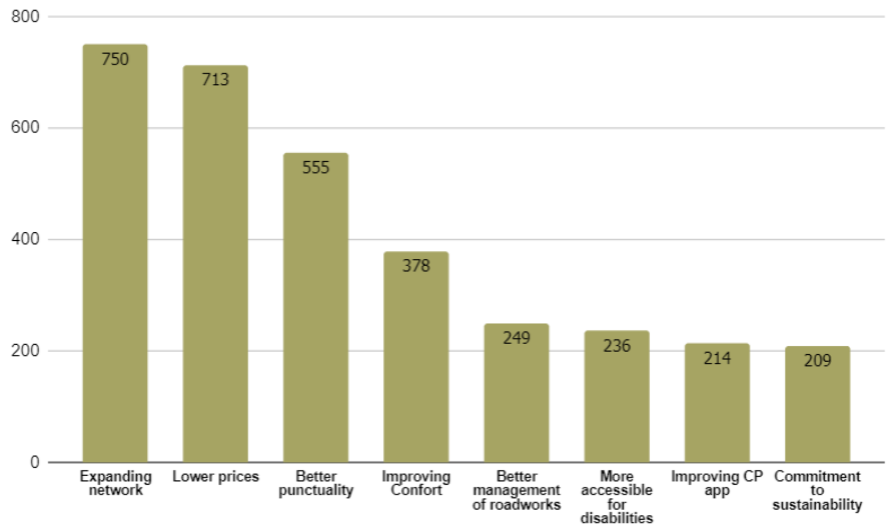


Figure 3.9: Top-rated Votes for Enhancing the Attractiveness of the Railway.

3.3.3 Summary of Findings

The examination of survey responses has produced numerous significant discoveries that offer valuable understanding into the present perceptions and priorities of railway users in Portugal. All of these conclusions are related to social responsibility in some manner. While not often immediately connected, all of these initiatives are ultimately focused on promoting social welfare or, at the very least, implementing internal reforms that prioritize social and economic responsibility.

The minority of passengers are older individuals. This implies the existence of a demographic disparity in the frequency of railway service usage, highlighting the need for focused efforts to reach and engage specific groups. The data also indicates a correlation between passengers' income and their utilization of railways, with higher wages being linked to less frequent use of train transportation. This suggests that the decision-making process for higher-income individuals when choosing transportation is influenced not only by affordability, but also by factors such as comfort and reliability.

Another notable discovery is that the majority of participants lack awareness regarding promotional initiatives associated with Portugal's railway system. This presents a chance for railway operators to bolster their marketing endeavors and enhance the visibility and communication of promotional initiatives in order to raise awareness and attract more passengers. This will result in increased client acquisition as well as the development of new client relationships, while also fostering a certain level of client loyalty.

The respondents hold a firm belief that dependable rail services play a significant role in promoting territorial cohesion and connectivity in Portugal. Furthermore, they believe that the presence of railway infrastructure in every district capital fosters both economic growth and social integration. These perceptions highlight the wider societal importance placed on a strong and dependable railway system, which is a key component of Social Responsibility.

In addition, many participants highlighted the significance of reducing the expense of train travel. They proposed that offering discounts and lowering ticket prices could attract a wider range of passengers and improve overall satisfaction.

Respondents expressed a significant level of concern regarding reliability. The majority of participants expressed a preference for using cars and buses rather than trains for a significant portion of their journeys due to the lack of control over departure and arrival times, which is frequently caused by delays resulting from strikes or rail maintenance operations. This underscores the necessity of enhancing the dependability and timeliness of train services in order to render rail travel a more appealing choice. Additionally, it is important to prioritize the well-being of railway employees to prevent strikes and enhance the reputation of this transportation system for its dependability.

Other suggestions put forth by participants call for improved integration of trains with other modes of transportation. Recommendations encompass enhancing the availability of parking amenities and establishing shuttles that connect stations to prominent nearby destinations. An innovative suggestion was put forward to integrate a "ferry" service into the train system, enabling the transportation of cars as cargo alongside passenger cars. The respondents' desire for a more versatile and integrated transportation system is reflected in this innovative idea.

Surprisingly, the level of commitment to the environment was found to have some influence on voting, although it was less significant compared to ticket prices or network expansion. This indicates that although sustainability is a significant worldwide problem, it may not be the foremost priority for the majority of present railway users in Portugal. This may suggest a requirement for enhanced awareness and education regarding the ecological advantages of railway transportation, or it could indicate that respondents prioritize immediate, pragmatic concerns such as cost and reliability.

Many passengers are still linked to negative past experiences within the railways' services. To address this, the railway system should implement a strategy focused on rebuilding trust and improving satisfaction. This includes understand specific concerns, enhancing customer service, and ensuring transparent communication about service improvements. Promoting positive experiences and introducing reward programs could further help to rebuild trust and encourage greater use of rail services.

3.4 Benchmark of Social Responsible Business Practices within Foreign Railways

This subsection undertakes an analysis of case studies and articles in order to assess noteworthy social responsibility initiatives implemented by international railway networks. In the field of social responsibility, which encompasses social, economic, and environmental elements, the objective of this evaluation is to identify successful approaches, innovative strategies, and best practices employed by foreign railway companies and that may be applicable to the railway sector in Portugal.

In a case study by Nedeliakova et al. (2020), R606 express train delays at specific stations along the principal railway corridor of the Slovak Republic are examined. State-owned carrier operates the train. This proposition revolves around the utilization of Lean philosophy in the context of risk management, specifically as it pertains to train delays in passenger rail transportation.

Constant improvement is a fundamental action in the pursuit of excellence in passenger rail transportation. Hence, it is imperative to comprehend the specific mechanisms associated with risks in every transportation endeavor. There are numerous tools available on a global scale that facilitate the analysis and comprehension of processes and services in great depth (Topfer, 2008).

Lean principles in the railway industry emphasize the efficient production of high-quality goods in order to satisfy customer demands (Yerubandi et al., 2019). It entails the ongoing surveillance and enhancement of quality in order to preserve customer loyalty and competitiveness.The utilization of Lean methods in risk management for train delays in railway passenger transport is intended to identify, classify, and investigate hypotheses.Lean philosophy's methodical approach facilitates the elimination of waste, the realization of value-adding processes, and the reduction of quality variation, thereby ensuring conformity with customer specifications.

The findings of this case study (Nedeliakova et al., 2020) underscore the importance of implementing a methodical approach to address train delays and underscore the advantages of implementing the Lean philosophy for efficient risk management.The research findings were not solely beneficial for railway enterprises in Slovakia, but also for railway organizations in countries classified as V4, including Poland, Hungary, and the Czech Republic. Although situated in distinct contexts, Portugal and Slovakia share common obstacles within the railway industry, including but not limited to regulatory compliance, efficiency enhancements, and infrastructure maintenance. Portugal has the potential to achieve enhanced operational efficiency, cost reduction, and adherence to European Union directives through the deployment and modification of the management strategies that were identified in the research. In addition, facilitating collaboration and the exchange of knowledge among railway organizations in Portugal and Slovakia affords prospects for cross-border cooperation and mutual learning within the European railway community. Hence, the implementation of the research outcomes in Portugal may foster greater integration with European railway standards and practices and contribute to the development of the country's railway industry.

An additional pertinent case study is presented by (Cavallaro and Nocera, 2023), which examines the difficulties associated with public transportation services in rural regions of Italy, with an emphasis on issues of accessibility and efficiency. The paper presents Demand-Responsive Transport (DRT) as a prospective resolution, highlighting its capacity to accommodate the requirements of rural communities through its temporal and spatial adaptability. Furthermore, the research suggests that passenger and freight transportation could be merged in order to optimize operations and decrease expenditures, especially in rural areas where traditional public transportation systems are inadequate to accommodate the population.

I-DRT, a conceptual framework proposed by the study, integrates freight and direct passenger transportation. The performance of this framework is assessed through the utilization of key performance indicators (KPIs). Mageean and Nelson (2003) evaluates how the integration of passenger and freight transportation in rural regions can result in substantial advantages, such as increased service frequency and decreased operational expenses. This integration also effectively tackles obstacles associated with insufficient accessibility and limited resources.

The study proposes that the integration of freight and passenger transportation could result in improved user perception of the service, in addition to potential financial and environmental benefits (Van Duin et al., 2019). The I-DRT framework provides enhanced market customization, adaptability to user needs, and flexibility in managing vehicle fleets. As a result, it is more cost-effective for users in comparison to private transport services (Bellini et al., 2003).

In order to ensure the success of the I-DRT system, legislative and policy support is necessary to surmount obstacles associated with the joint transportation of passengers and goods (Jansen, 2014). The framework that has been proposed is in accordance with the notion of Sustainable Urban Mobility Plans. It offers a strategic outlook on how to incorporate I-DRT into mobility planning in order to enhance territorial accessibility as a whole (Rupprecht Consult, 2019).

Fundamentally, the implementation of the I-DRT framework could yield favorable environmental outcomes, cost reductions, and enhanced transport services for rural regions. Moreover, the study's findings and advantages may be extrapolated to other railway systems, including that of Portugal, thereby providing a comprehensive strategy for tackling issues related to accessibility and efficiency in rural public transportation.

An additional investigation discovered (Killen et al., 2018) explores the prospective implementation of additive manufacturing (AM) within the rail sector. It investigates how AM could be utilized to optimize the design, production, and maintenance of a variety of customer-facing and internal rail sector components. The study evaluates the potential benefits and drawbacks, as well as the economic feasibility and production cycle duration, of integrating AM technology into rail operations.

The study identifies the economic benefit of utilizing AM for rail component manufacturing as one of its primary advantages. Conventional manufacturing techniques frequently necessitate the use of costly tooling, resulting in substantial initial expenditures. Conversely, augmented reality eases the fabrication of customized components and prototypes without requiring costly tooling, thus diminishing initial investment expenditures. Particularly significant for small to medium production volumes and complex or customized parts, where AM can provide cost-effective solutions (Petrick and Simpson, 2013). Moreover, additive manufacturing obviates the necessity for extensive component stockpiling, as it enables on-demand component production that reduces inventory expenses (Kietzmann et al., 2015).

An additional benefit of AM technology is its adaptability and swiftness during the manufacturing phase. In contrast to conventional manufacturing approaches, which often necessitate the involvement of numerous suppliers and intricate supply chain integration, additive manufacturing enables the internal fabrication of components using digital CAD files. The streamlined production process facilitates quicker iteration and customization of designs by decreasing lead times and operational complexities (Alpern, 2010). In addition, additive manufacturing (AM) provides substantial material versatility, enabling the fabrication of components from an extensive array of substances such as metals, polymers, ceramics, and composites. This adaptability improves the functionality of prototypes and finished goods and broadens the scope of design possibilities (Berman, 2012).

Additionally, rapid prototyping and iterative design improvements are facilitated by AM technology, resulting in improved user experience and product development. AM enables rail operators to generate prototypes for iterative user testing, which facilitates the incorporation of practical feedback and the enhancement of designs. The implementation of this iterative methodology expedites the process of product development and empowers rail operators to sustain competitiveness amidst a dynamic market environment (State of Victoria, 2017).

Portuguese rail operators could experience the same benefits outlined in the study through the implementation of AM technology: decreased production costs, accelerated prototyping, and enhanced supply chain management. Furthermore, the adaptability and personalization provided by AM may empower Portuguese rail operators to more effectively cater to the unique requirements of their clientele and respond to shifting market dynamics. In general, the incorporation of additive manufacturing (AM) technology into the rail sector of Portugal has the potential to improve the industry's sustainability, competitiveness, and service quality. This would be consistent with the country's overarching objectives of fostering innovation and increased efficiency in public transportation networks.

An additional pertinent article (Coviello et al., 2023) centres on the Automatic Timetable with Multiple Objectives (ATMO), an innovative tool designed and implemented by the Railway Directorate of Norway to generate railway timetables. The principal objective of this instrument is to optimize strategic planning in the railway industry through the streamlined conversion of theoretical service demands into operational schedules, with a focus on minimizing time wastage and ensuring reliability. The study underscores the significance of strategic planning in the realm of railway operations, specifically with regard to Norway's ambitious goals, which include attaining climate neutrality by 2050 and converting a substantial proportion of freight transportation to rail and maritime modes by 2030.

The strategic planning of the railway industry entails intricate decision-making procedures that require a careful equilibrium to be maintained among infrastructure capacity, rolling stock availability, and train scheduling. Conventional approaches to timetable development frequently demand significant effort and duration, entailing iterative cycles of design, simulation, and modification. The objective of implementing the ATMO tool is to enhance efficiency in this procedure through the utilization of cutting-edge mathematical optimization methods for the generation of optimal timetables. The ATMO tool utilizes a mixed integer linear programming algorithm in conjunction with ant colony optimization to achieve a multi objective result. By employing this approach, a diverse array of schedule alternatives can be examined, taking into account multiple goals including the reduction of travel duration, the enhancement of dependability, and the optimization of capacity utilization. The instrument effectively supports strategic planning decision-making by furnishing planners with a collection of viable timetables as opposed to a singular solution.

The merits of the ATMO instrument are illustrated by means of an exhaustive case study performed on the Bergen–Oslo rail line in Norway. The research assesses various service concepts and infrastructure scenarios in order to determine freight train schedules that minimize additional travel time while maximizing scheduling without any conflicts. The outcomes underscore the tool's capacity to generate a substantial quantity of viable schedules in an efficient manner, thereby empowering planners to effectively evaluate alternative infrastructure designs and service concepts.

In general, the research emphasizes the importance of sophisticated planning tools such as ATMO in effectively tackling the intricate obstacles encountered by contemporary railway systems. Through the utilization of mathematical optimization and simulation methodologies, these tools grant railway authorities the ability to formulate timetables that are both efficient and robust, thereby ultimately augmenting the overall performance and competitiveness of railway services.

Overall, the examination of different case studies and research articles highlights the complex and varied nature of innovation in different sectors. Similarly, the implementation of inventive tactics highlights the cooperative method required to tackle intricate environmental problems. Moreover, the ability of these solutions to grow and adjust is demonstrated through comparing them in various geographical settings, ranging from cities to rural areas. These case studies provide inspiration and guidance for future endeavors aimed at achieving sustainable growth and inclusive development, as industries adapt to technological advancements and societal demands.

3.5 Legal Framework

The legal framework regulating the adoption of a social responsibility business model in the railway sector is complex and includes a broad spectrum of national as well as international rules. The purpose of this chapter is to provide an overview of the essential legal factors that need to be taken into account for the business model.

3.5.1 National Regulation

The *Instituto da Mobilidade e dos Transportes (IMT)* is responsible for the main laws that regulate railway safety in Portugal. Here are certain important regulations to take into account:

- **Decree-Law No. 270/2009** establishes the safety regulations for railway operations in Portugal, including the specifications for materials utilized in the construction and renovation of railway vehicles (Government of Portugal, 2009a).
- The **IMT Technical Specifications** outline the exact criteria for the performance of materials used in interior applications, with a particular emphasis on their durability, fire resistance, and environmental impact (Instituto da Mobilidade e dos Transportes, 1998).
- **Decree-Law No. 178/2006** on Waste Management requires the appropriate disposal and recycling of trash, while encouraging the utilization of sustainable and recyclable materials in industrial settings (Government of Portugal, 2006).
- **Decree-Law No. 152-D/2017** (Environmental Impact Assessment) mandates the evaluation of the environmental impact of any substantial alterations in material usage within the railway industry. This evaluation ensures that new materials align with sustainability objectives (Government of Portugal, 2017).
- **Decree-Law No. 89/2009** promotes the adoption of corporate social responsibility (CSR) principles by firms, which encompass environmental sustainability, community participation, and ethical labor practices (Government of Portugal, 2009b).

3.5.2 European Union Directives

- The **Railway Interoperability Directive (2008/57/EC)** sets out the requirements for ensuring compatibility and cooperation across the European railway system. It specifically addresses the technical and operational aspects of railway infrastructure, rolling stock, and sub-systems. Specifically, Article 4 highlights the significance of safety and environmental preservation in the process of choosing materials. Additionally, Annex III provides a comprehensive list of fundamental criteria for materials utilized in railway cars, encompassing fire safety, mechanical durability, and recyclability (European Parliament and Council of the European Union, 2008).
- The **REACH Regulation (EC 1907/2006)** is a regulatory framework that seeks to guarantee a superior degree of safeguarding for human health and the environment against the potential hazards presented by chemicals. Its main objectives are the registration, evaluation, authorization, and restriction of chemicals. Specifically, Article 31 mandates suppliers to furnish safety data sheets for all chemical substances employed in products. Additionally, Annex XVII enumerates limitations on specific hazardous substances that are prohibited from being

utilized in railway applications (European Parliament and Council of the European Union, 2006).

- **EN 45545-2-R1** standard outlines the fire performance specifications for goods and materials used on railroad cars. The R1 variant applies only to interior surfaces and needs to be thoroughly tested for toxicity, smoke emission, and flammability (European Committee for Standardization, 2013).
- The **European Green Deal** seeks to achieve economic sustainability in the EU by transforming climatic and environmental issues into advantageous prospects. It provides incentives for European Union countries to establish many new high-speed connections throughout Europe, with the aim of boosting train usage and potentially reducing CO2 emissions by 89% (European Commission, 2019).

3.5.3 International Certification

- **ISO 4589-2:** Defines procedures for figuring out the lowest oxygen content necessary to enable plastics to burn (International Organization for Standardization, 2017).
- **ISO 9239-1**: This standard describes how flooring responds to fire tests and is relevant to interior panels in railroad cars (International Organization for Standardization, 2010b).
- **ISO 14040/14044:** These guidelines deal with life cycle assessment (LCA), which is essential for determining how the materials being used will affect the environment (International Organization for Standardization, 2006).
- **ISO 5658, ISO 5660-1, and ISO 5659-2:** These are the particular test procedures that EN 45545-2 refers to in order to assess flame spread, heat release rate, smoke density, and toxicity, in that order (European Committee for Standardization, 2013). More precisely, the case study presented in the following chapter will employ two of these tests—ISO 5660 and ISO 5659—to determine the fire resistance characteristics of the evaluated materials.

3.6 Implementation

This chapter outlines the materialization of the insights gathered from the survey responses. The plan focuses on key areas for improvement identified through the survey (expanding the railway network, reducing ticket prices, enhancing reliability, integrating different modes of transportation, and addressing the lower priority given to sustainability) but will also include strategies for monitoring progress, ensuring continuous improvement, and effectively communicating changes to stakeholders.

It is crucial to acknowledge that the implementation of the suggested enhancements to Portugal's railway system requires careful examination of the legal framework that governs different areas of transportation and social responsibility.

3.6.1 Survey-Based Proposals

In light of the survey results, particular enhancements might be executed, including the investigation of dynamic pricing models to provide more cost-effective alternatives during periods of low demand. Additionally, enhanced discount programs catering to senior citizens, students, and frequent travelers could be implemented, given that the existing ones fail to substantially augment the clientele. Moreover, infrastructure planning enhancements should be funded in order to reduce delays caused by maintenance issues.

While it is possible to implement operational efficiency measures to mitigate the effects of strikes and other disruptions, enhancing working conditions provides the highest level of security.

Implement dependable and real-time updates to passengers concerning train schedules and any potential delays; this could be accomplished via social media or the CP app, for instance.

In addition to establishing transit services to connect train terminals with important destinations (airports, business districts, and tourist attractions), the implementation of multi-modal ticketing options can be implemented to streamline the journey when utilizing various modes of transportation.

Engaging through events and campaigns and collaborating with environmental organizations to promote sustainability initiatives could be the primary approaches to addressing the issue of sustainability awareness.

3.6.2 Monitoring and Continuous Improvement

Efficient monitoring is crucial for monitoring the advancement of the implementation strategy and verifying that the enhancements are producing the intended results. It is important to establish Key Performance Indicators (KPIs) in order to measure the success of each improvement initiative. Suggested KPIs are:

- **Ticket Pricing:** Changes in ticket sales volume, passenger satisfaction ratings regarding affordability.
- **Reliability:** Frequency and duration of delays, number of complaints related to punctuality, Frequency of strikes and their causes.
- **Integration:** Usage rates of parking facilities and shuttle services, passenger feedback on transportation links.
- **Sustainability:** Passenger awareness, usage of eco-friendly initiatives, carbon footprint.

It is necessary to produce regular reports in order to evaluate the progress made in relation to the KPIs. A dedicated monitoring team must review these reports and share them with stakeholders to guarantee transparency and accountability. The current situation regarding the delay in publishing the accounts and sustainability reports must be avoided.

Continuous feedback mechanisms, such as conducting passenger surveys and providing suggestion boxes, could be implemented to consistently collect input from railway users. The provided feedback will be carefully examined to detect any emerging concerns or potential areas that require additional enhancement.

3.6.3 Communication Strategy

Effective communication is essential for the implementation of enhancements to be successful. In the context of internal communication and staff meetings, periodic staff meetings shall be convened to provide updates on progress and solicit their input. Staff should also be provided with monthly newsletters that detail current and forthcoming initiatives.

To address the issue of passengers being unaware of campaigns, there is a need for an overall enhancement in the marketing strategy for external communication. Specifically, consistent updates shall be disseminated to the general public via official railway website as it is done today, but also by social media platforms, press releases and advertisement. In this case, passengers will be the target audience of information campaigns that detail the ongoing enhancements and their anticipated benefits.

3.7 Risk Analysis

This work aims to enhance social responsibility, sustainability, and transportation services throughout Portugal's railway system. This program is comprised of thorough study, which includes analyzing survey data and comparing it to international best practices in railway management. Although the proposed enhancements provide great potential for improving Portugal's railway infrastructure, they also come with some risks that need to be thoroughly assessed and controlled to ensure successful execution. This risk study offers a methodical evaluation of the potential hazards linked to the suggested improvements, taking into account their probability of happening and their potential consequences on the railway system and those involved.

The risk analysis table presented below offers a thorough summary of the potential risks linked to the execution of improvements to Portugal's railway infrastructure. Every risk is assessed according to its probability of happening and the effect it would have on the project. Furthermore, the final column denotes the hierarchy of significance of the detected threats, ranging from the most crucial (1) to the least crucial (8), based on the combination of likelihood and impact. This column enables the reader to allocate their attention and resources to dealing with the most noteworthy dangers initially, guaranteeing that efforts to reduce these risks are directed efficiently.

The selected risks pertain to all possible occurrences that could happen during or following the investment for the implementation of the new measures. It is crucial to acknowledge that certain risks are already probable to occur today, but that does not imply that they should not be addressed.

Table 3.3: Risk Analysis to the Execution of Improvements to Portugal's Railway Infrastructure.

Risk	**Description**	**Likelihood of Occurrence**	**Impact**	**Order of Importance**
Regulatory Compliance Risk	Risk of failure to comply with regulatory requirements and standards, leading to legal penalties or delays in implementation.	Low	Medium: Non-compliance could result in legal fines, or delays in implementation, impacting the overall progress of the railway system.	8
Financial Risk	Risk associated with financial investments in infrastructure and initiatives, including cost overruns or inadequate returns.	Moderate	High: Investing in infrastructure and projects can exceed the budgeted costs or generating insufficient returns, which might impact the financial sustainability.	1
Operational Risk	Risk of operational challenges technical failures, or construction issues disrupting services and affecting customer satisfaction.	High	Medium: Operational challenges such as technical failures, or coordination issues could disrupt services and affect the reliability of the service and consequently, customer satisfaction.	2
Labor Relations Risk	Risk of tensions with labor unions or employee resistance leading to disruptions in operations.	High	Medium: Tensions with labor unions or employee resistance could lead to disruptions in operations, impacting service reliability and customer satisfaction.	3

Customer Acceptance Risk	Risk of resistance to fare modification or skepticism about service improvements affecting passenger numbers and revenue.	Moderate	Low: Resistance to fare modification or skepticism about service improvements could affect passenger numbers and revenue, impacting the financial performance.	6
Environmental Risk	Risk of unforeseen environmental challenges affecting the feasibility or effectiveness of sustainability initiatives.	Moderate	Medium: Unforeseen environmental challenges or regulatory changes could affect the feasibility or effectiveness of sustainability initiatives.	5
Technological Risk	Risk of technological challenges such as software glitches or cybersecurity vulnerabilities disrupting operations and compromising safety.	Low	Medium: Technological challenges could disrupt operations and compromise passenger safety.	7
Reputational Risk	Risk of failures to deliver on promised improvements or negative media coverage damaging the reputation of railway operators.	Moderate	Medium: Failures to deliver on promised improvements or negative media coverage could damage the reputation of railway operators, leading to loss of customer trust.	4

3.8 Brief Summary of the Framework

The summary of each stage in this framework is provided below in Figure 3.10.

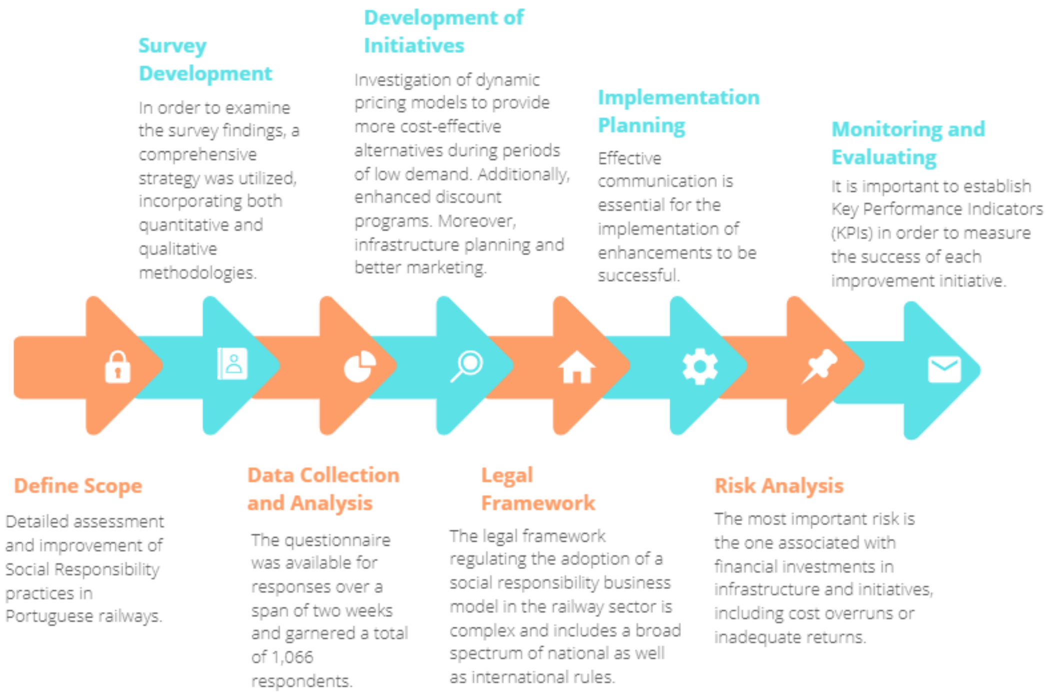


Figure 3.10: Brief Summary of the Framework

Chapter 4

Case Study

4.1 Introduction and Overview

The prioritization of social responsibility is now recognized as a significant key point in diverse sectors, including the field of mechanical engineering. Given the significant environmental impact and socioeconomic importance of Portugal's railway sector, it is crucial to prioritize the implementation of environmentally beneficial practices. The choice of materials is crucial in this attempt, as it has significant implications for environmental preservation, business efficiency, and social responsibility.

This case study has two main purposes: firstly, to underscore the significance and possibility of choosing sustainable materials in promoting environmentally conscious engineering practices; and secondly, to establish a study for assessing unconventional material solutions in the context of Portuguese railways. The study's methodology is largely influenced by the principles described in Michael Ashby's work on materials selection (Ashby, 2011), thus providing a systematic approach that is firmly rooted in engineering principles and environmental standards.

The work entails a thorough assessment of currently obtainable and sustainable materials, taking into account variables including recyclability, acquisition and innovation. Following this, a series of laboratory experiments and practical trials were undertaken to assess some mechanical properties and other critical performance indicators of the materials that have been chosen. These tests guarantee adherence to the rigorous safety and quality criteria that surround the railway sector.

Although it is important to evaluate and analyze the recyclability of selected solutions to promote sustainability, it is critical to acknowledge that recycling is merely the last phase in the lifespan of materials. Sustainable material selection involves taking into account the complete life cycle of a material, including its several uses and only then the disposal. Hence, although recyclability holds significance, it is only a single element of a broader sustainability approach. Factors like potential for re-purpose and biodegradability also have substantial influence in determining the overall sustainability of materials. By adopting a comprehensive approach to choosing materials and considering the full life cycle, including considerations beyond just recyclability, it is possible to make well-informed choices that reduce environmental harm and support long-term ecological accountability in the design of railway interiors. Given this, the main intention of this case study is to identify a solution that either derives from natural sources, such as natural fibers or a natural matrix, or has a positive ecological impact at the conclusion of its life cycle.

4.2 The Current Solution

There is a lack of documentation regarding the present panels utilized on the trains in Portugal, as they were imported more than 30 years ago. However, for the purpose of comparison, two examples are provided: the panels found on Dutch trains and the panels that are under study for the intended use in the Innovation Pact "PRODUCING RAIL CIRCULATING MATERIAL IN PORTUGAL" project.

The current side wall panels of Dutch trains, starting from VIRM-1 in 1994 (similar to the Portuguese trains used for suburban services in the Lisbon Metropolitan Area), are constructed using a composite material involving unsaturated polyester resin reinforced with glass fibers. Glass fibre composites are typically lightweight materials that can acquire fire retardant properties when appropriate additives are used (Mistry et al., 2020). This property makes it a suitable material for utilization in train applications, hence ensuring a prolonged lifespan for the panels. The duration of its life-cycle, from inception to termination, is approximately 15-20 years (Van Oudheusden, 2020) and its main problem is the end of life stage.

In the Innovation Pact "PRODUCING RAIL CIRCULATING MATERIAL IN PORTUGAL" project, the proposed solution is flame-retardant polycarbonate (PC), which does not exhibit biodegradation. However, there are no anticipated adverse environmental consequences. It may be recycled or disposed alongside household waste. Additionally, it provides a dependable long-term application.

The design of the panel may vary depending on the train being analyzed, as depicted in the Figure 4.1 below.

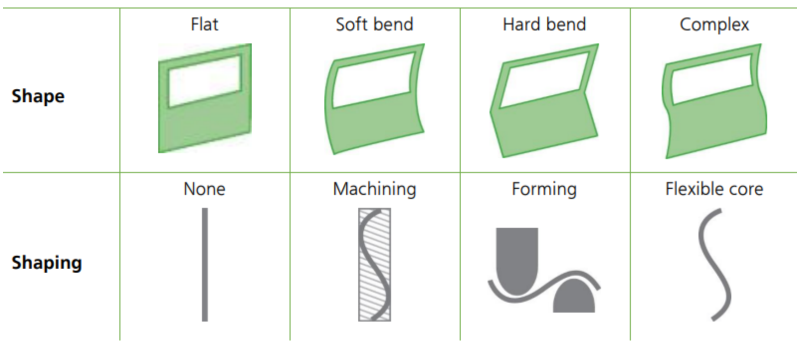


Figure 4.1: All the Different Configuration Options for the Side Wall Panel Walls, adapted from Van Oudheusden (2020)

Following the initial usage cycle, the material retains sufficient residual value to warrant consideration for a subsequent usage cycle. This item has the potential to be utilized again within the train or repurposed for usage outside of the train. However, it is currently challenging to implement this second use cycle. During the modernization process, the train's interior is updated, which may result in a mismatch between the new design and the old panels. For instance, if something is deemed to have an incorrect hue or lacks the desired visual appeal. The reconfiguration of the panels necessitates their adherence to the updated safety rules, including those pertaining to fire safety.

These regulations undergo frequent revisions, increasing the likelihood that the old panels may not receive approval. Adapting the panels located outside the train for a different purpose is difficult due to their highly specialized shape, and it is not possible to reshape the thermoset material they are made of. Once the panel has served its role in train modernisation, it will no longer be usable or adaptable, thereby reaching its end-of-life. Currently, the composite panels are discarded and sent to a landfill. Currently, it is not practical to recycle the material or its resources on a large scale in a manner that allows for their reuse in the same application.

Additionally, the cost of new glass fibre is significantly lower than that of the lower-quality recycled fibres, making it difficult for the recycled fibres to remain competitive. Frequently, while "recycling" composite materials, the substance is incinerated or fragmented, and the remaining residue is utilized as a filler in other substances. This implies that a significant portion of the material value is diminished, rendering it an unsuitable choice for a circular economy (Van Oudheusden, 2019). Undoubtedly, recycling technologies may continue to evolve in the future, yet composite materials have already existed for a significant duration. Hence, anticipating this transformation does not align with the leading role that the United Nations aspire to assume in the circular economy (United Nations, 2023). An alternative that is circular and recyclable is required.

4.3 Constraints Definition

As stated before, the study's methodology is largely influenced by the principles described in Michael Ashby's work on materials selection (Ashby, 2011). According to his work, the material selection process involves identifying the optimal match between the intended attribute profile and those of actual engineering materials.

Translation is the initial stage in approaching selection. It consists of analyzing the design specifications to determine the limitations they place on material selection. The extremely vast selection is initially reduced by eliminating the materials that fail to satisfy the specified criteria. The candidates are now further refined through a ranking process based on their capacity to optimize performance. In the last process, selection, the optimal correspondence between the specified property profile of the design and the property profile of the materials available is achieved.

The use of traditional materials in these panels, including composites and polymers, presents noteworthy ecological obstacles on account of their dependence on fossil fuels, lack of biodegradability, and energy-intensive production procedures. To combat this trend, it is imperative to integrate the concepts of recyclability and acquisition (Struck and Flamme, 2023) alongside the functional requirements.

Following Michael Ashby's approach on material selection (Ashby, 2011), it is necessary to methodically outline the design requirements for selecting any material in any sector. The process involves identifying the purpose of the component, crucial limitations, goals to be optimized or minimized, and the identification of free variables. By following this systematic methodology, it guarantees a thorough assessment of material alternatives that adequately satisfy the functional, performance, and, in this particular instance, sustainability standards.

The primary purpose of the interior panels found in railway vehicles is to offer durability, insulation, visual attractiveness, as well as fire resistance, lightweight construction, soundproofing capabilities, and enhancement of thermal comfort (UNIFE, 2014). Considering these factors, one can identify crucial limitations such as impact resistance,fatigue resistance, fire resistance, dimensional stability, ecological responsibility, weight, and thermal inertia. Following United Nations (2023), another overall goal of this process is reducing environmental impact and life cycle costs. Unconstrained variables include factors such as the composition of materials, production methods, and geometric arrangements.

The next subsections will carefully analyze each constraint.

4.3.1 Design

Opting for a flat panel configuration enhances its ability to reshape, facilitating its adaptation for reuse in other trains or re-purposing applications, hence enhancing the panel's circularity. By partitioning the bottom section, the window section can be modified independently for use in another train or for maintenance and repairs (Van Oudheusden, 2020). Considering this, the panels could be presented in two primary formats, as depicted in the Figure 4.2 below. This design is versatile and may be adjusted to fit different areas with dimensions. For the sake of comparison, the modules of the current Dutch train fleet range from 1630 to 3400 mm in width and 1220 to 1510 mm in height (Van Oudheusden, 2020).

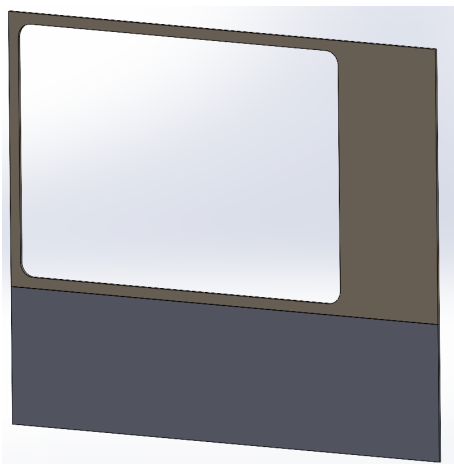


Figure 4.2: Shape Configuration Designed in SolidWorks ®, Where the Partitioning of the Bottom Section is Seen.

4.3.2 Mechanical Properties

Understanding the mechanical constraints is crucial in assessing the suitability of materials for interior panels in railway vehicles. The load requirements outlined in UNIFE (2014) are limited to the ability to endure: "a concentrated perpendicular load of 2.0 kN applied over a symmetric area of not more than 0.01 m^2 which may occur at any position on the surface". In addition to the aforementioned, the subsequent mechanical requirements are deemed significant through the analysis of articles on the matter (stated bellow near each requirement) and the technical report by UNIFE (2014):

- **Fatigue Resistance:** the fatigue resistance of materials used in railway vehicle interior panels is of the greatest significance due to the repetitive stress they experience. In order to provide long-term durability, panels need to have the capacity to withstand vibrations, accelerations, and deceleration, hence requiring resistance to both high and low cycle fatigue Tang et al. (2021). Materials must have the ability to endure multiple stress cycles without experiencing failure, and fatigue resistance is influenced by characteristics such as grain size and flaws (Santulli, 2019). The maintenance of structural integrity and extension of panel lifespan are contingent upon the assurance of fatigue resistance (Tang et al., 2021), making it a crucial parameter consistently evaluated in tests for new materials for railway application, as seen in some articles on the matter (Robinson, 2016).

- **Weight Considerations:** light weighting is a prevalent theme in railway vehicle design, as reducing weight can enhance operational efficiency and energy savings. Composite materials offer significant mass savings while maintaining or improving structural efficiency. Studies on lightweight design alternatives (De Silva, 2018), (Mistry et al., 2020) reiterate the importance of reducing the primary energy demand during operation, thereby supporting the creation of more energy-efficient railway vehicles.

- **Shapability:** the malleability of materials used in railway vehicle interior panels is a crucial factor to consider. In terms of space inside the train, curved materials can be advantageous for saving space, especially in areas like windows where thickness can impact available space. However, it's essential to note that while a curved shape may optimize space utilization, a flat shape offers advantages in terms of ease of reshaping. A flat shape is generally easier to manipulate and reshape, facilitating reuse in other trains or re-purposing applications (Van Oudheusden, 2020). Given these considerations, malleability may be a factor of lower importance in the selection index compared to other criteria because the importance of space savings cannot be overlooked, and a balanced approach is necessary to ensure both functionality and environmental responsibility.

4.3.3 Fire Resistance

Standardized tests are done to completely evaluate the fire performance of materials, with each test serving a unique function. The EN 45545-2 R1 standard, which is specifically designed for internal surfaces on trains and is marked by the "R1" designation, assesses the fire performance of materials based on strict criteria. The assessment evaluates essential variables including flame propagation, thermal dissipation, smoke density, and degrees of toxicity. Adherence to EN 45545-2-R1 is mandatory for materials utilized in railway interiors, guaranteeing their compliance with the stringent criteria for fire resistance as demonstrated by the subsequent tests (UNIFE, 2014).

- **ISO 5658 (Spread of Flame Test):** this test measures the propensity of materials to support the rapid spread of flame across their surface. By quantifying the material's flammability, it provides valuable insights into its fire performance and suitability for railway applications.
- **ISO 5660-1 (Heat Release Rate Test):** this test determines the rate of heat release from materials when exposed to a radiant heat source. It helps assess the material's fire hazard potential by quantifying the amount of heat released per unit time.
- **ISO 5659-2 (Smoke Density and Toxicity Test):** this test evaluates the smoke density and toxicity levels emitted by materials during combustion. It is essential for assessing the health risks associated with smoke inhalation and ensuring the overall fire safety of interior panel materials.

4.3.4 Customer Comfort

Customer comfort is a pivotal consideration in the evaluation of materials for the interior panels of railway carriages. Thermal comfort, a significant component of overall comfort, plays a central role in ensuring passengers' satisfaction and well-being, as required in the *Train Technical Specification Document* by UK Government (2018) [1]. A crucial property to cover is the thermal inertia of the material. Thermal inertia relates to the intrinsic property of a material to withstand alterations in temperature, thereby impacting its capability to sustain consistent thermal conditions within the interior of a vehicle.

Materials that possess a high degree of thermal inertia demonstrate a reduced rate of temperature swings when subjected to external thermal perturbations. This attribute aids in maintaining stable interior temperatures, hence improving passenger comfort by reducing temperature fluctuations and fostering a more uniform thermal setting (Bozicek et al., 2023). Therefore, this attribute proves to be particularly advantageous during lengthy train rides or in different weather situations.

Furthermore, the utilization of materials possessing elevated thermal inertia might enhance energy efficiency through the mitigation of excessive heating or cooling requirements, thereby leading to a potential reduction in energy consumption and the subsequent decrease in associated expenses (Bozicek et al., 2023).

[1] The citation of a British government document is warranted here, as it reflects the widespread adoption of British standards within the European rail sector.

4.3.5 Acoustic Properties

Sound properties play a crucial role in ensuring passenger comfort and well-being. The design goal for interior noise can be defined based on three principles: firstly, compliance with applicable laws, regulations, or standards; secondly, meeting the specific requirements of customers; and thirdly, gaining a competitive edge in the market (ISO (International Organization for Standardization), 2011).

As per the regulations of China Railway Corporation, high-speed trains traveling at a speed of 350 km/h must conform to specific noise limitations within the train. These limits are set at a maximum of 79 dBA in the cab, 72 dBA at the coach end, and 70 dBA in the middle of the coach. In order to achieve the interior noise restrictions, it is necessary to strike a compromise between the consumers' demands and the benefits of market competition. The acoustic design of different types of carriages, such as business carriage and ordinary carriage, should be tailored to meet the specific requirements of clients. The Technical Specifications always contain the reflection. Cost containment is crucial for gaining a competitive edge in the market. The acoustic design should prioritize the critical regions and use the most efficient control techniques (Zhang et al., 2020).

The data inputs from previous studies (Fiedler et al., 2015), (Forssén et al., 2012) include carbody acoustic parameters, such as sound insulation, vibration damping and sound absorption, all of them further elucidated below.

- **Sound Insulation:** materials should provide adequate sound insulation to prevent the transmission of external noise into the passenger compartment and vice versa. The input parameters are Young's modulus, Poisson's ratio and density. Sound insulation materials include dense and heavy materials like mass-loaded vinyl, rubber insulators, and acoustic barriers (Zhang et al., 2020).

- **Vibration Damping:** materials with vibration damping properties can attenuate mechanical vibrations caused by vehicle motion, machinery operation, or external sources. The most important source of noise from railways is rolling noise, caused by wheel and rail vibrations induced by wheel/rail contact. Roughness on the wheel and rail running surfaces induce vertical vibrations of the wheel and rail systems (Juricka et al., 2020), as seen in the Figure 4.3. Vibration damping materials typically include visco-elastic polymers, rubber sheets, and damping pads. These materials dissipate mechanical energy by converting it into heat, effectively reducing vibration amplitudes.

- **Sound Absorption:** interior panel materials should have the ability to absorb sound energy, reducing reverberation and minimizing noise levels within the passenger compartment. According to Zhang et al. (2020), for sound absorption material, the input parameters are porosity, airflow resistivity, viscous characteristic length, thermal characteristic length and density. The good absorbent porous materials feature open-cell structures that trap sound waves and dissipate their energy as heat.

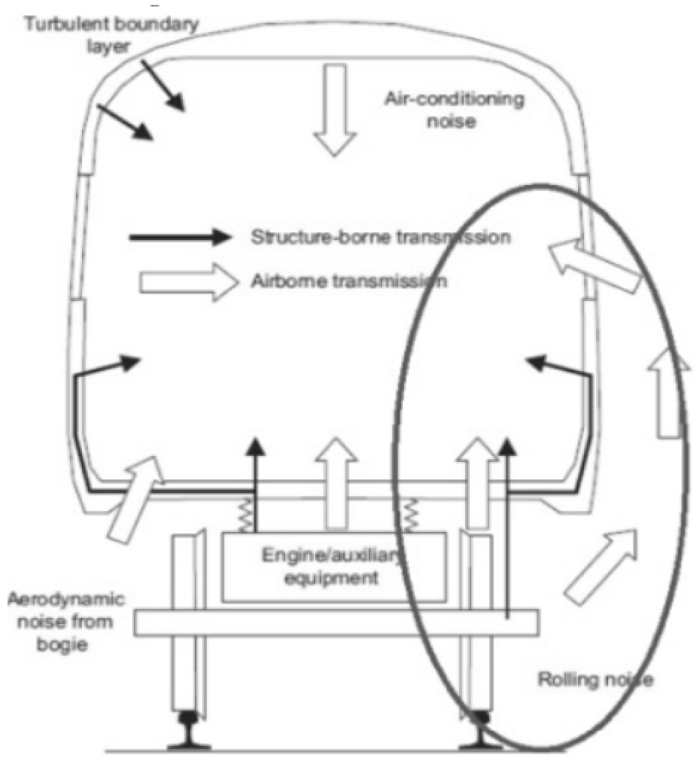


Figure 4.3: The Main Sources of Interior Noise in a Train and their Transmission Paths into the Vehicle (Juricka et al., 2020).

4.3.6 Recyclability and End-of-Life Management

As Delogu et al. (2017) state, despite having a minimal environmental impact, rolling stocks generate a significant quantity of End-of-Life (EoL) waste in relation to the number of vehicles, surpassing that of road vehicles. Due to the diverse nature of the components in railway vehicles, the end-of-life rolling stock is a valuable source of materials. Recycling these materials provides tangible economic and environmental advantages.

The recycling process becomes more effective and the recycling rate increases as the amount of materials treated in the dismantling stage increases. However, the time required for dismantling is a crucial aspect of the overall operation. Therefore, it is important to find a balance between the efficiency of recycling and the time it takes. Components that are extremely time-consuming to deconstruct should not be dismantled.

Recycling regulations have only been implemented for road transport modes, including passenger automobiles and light duty trucks. Regarding the railway sector, there is currently no formal legislation in place by international bodies or national governments (European Commission, 2022).

4.4 Material Candidates

This phase will slightly deviate from Ashby's recommendations, as the materials under investigation were selected due to the quest for alternatives that go beyond traditional thermoplastics. The following materials include a variety of ecologically conscious composites and bio-based alternatives, each possessing distinct features and characteristics tailored for railway applications. It is crucial to bear in mind that one of the main goals of this case study is to identify a solution that integrate sustainability features, whether through the use of renewable resources, recycled materials, or by offering green alternatives to conventional materials for construction.

Jute-Reinforced PLA Composite

Bio-composites made from a combination of jute fibers and polylactide (PLA) resin offer a sustainable and lightweight alternative for interior panel materials in trains. Jute fibers provide strength and stiffness to the composite while reducing overall weight. PLA resin acts as a matrix, binding the fibers together and providing additional mechanical properties. These bio-composites are environmentally friendly, renewable, and can be engineered to be flame retardant, making them suitable for this application. PLA is also biodegradable thus promoting a more positive end of life stage for the material. The use of this type of composites is started to be explored by the car industry with brands like Mercedes-Benz and Mitsubishi using them in their products (Robinson, 2016).

This material fulfills a significant portion of the study's objectives; therefore, it was determined to continuously observe the initial stages of its life cycle by producing samples exclusively for this investigation (Figure 4.4).

Figure 4.4: Jute Fibers Embedded in PLA Matrix.

Material A

Material A is an engineered wood product that combines wood fibers with organic dyes and resins (Figure 4.5). This composite material offers excellent mechanical properties, including high strength and dimensional stability, making it suitable for interior panels in railway vehicles. Material A is also environmentally friendly, as it is manufactured from recycled wood fibers and formaldehyde-free binders, aligning with sustainability objectives. Additionally, some formulations of Material A offer inherent fire resistance, providing an added layer of safety in railway interiors. The historical trains use wood panels, therefore choosing this type of material is not lacking context.

Figure 4.5: Material A Sample.

Material B

Material B is a composite panel made up of a blend of wood particles and cement (Figure 4.6). It merges the pliability of wood with the robustness and endurance of cement, enabling a diverse array of uses in both interior and exterior settings. Boards can undergo cutting, drilling, and machining processes using power or compressed air tools that are frequently employed in carpentry or mechanical metalwork.

After engaging in discussions with several suppliers, only a select few provided a response, leading to the identification of the following candidates: two materials, referred to as Material A

Figure 4.6: Material B Panel.

and Material B for commercial reasons. The jute+PLA composite was deployed to promote an interactive project that involved the complete production cycle, from sourcing the raw materials to producing and testing the final material. All three of these options provide environmentally sustainable alternatives that have the potential to comply with safety criteria for railway interiors. Consequently, the research has found three robust candidates, while dismissing often employed alternatives like epoxy composites.

Epoxy resins, which are made from petrochemical sources, necessitate production methods that consume a significant amount of energy. Moreover, these composites frequently include hazardous additives and present difficulties in recycling, which give rise to environmental worries and complicate the process of disposing them at the end of their lifespan.

Aside from epoxy resins, other often employed options for lightweight composite materials include carbon fiber reinforced polymers (CFRP), fiberglass reinforced polymers (FRP), and aramid fiber reinforced polymers (AFRP). Although these materials possess exceptional mechanical qualities and contribute to weight reduction, their intricate composite structure poses difficulties in terms of recyclability. Although the polymer matrix in these materials can be partially recycled, the inclusion of fibers (carbon or glass) adds complexity to the recycling procedure. Specialized processes and significant amounts of energy and resources are necessary to separate the carbon fibers from the epoxy matrix for recycling purposes, resulting in high costs. Despite various attempts to create recycling techniques, they are not as simple, effective or cheap as the recycling processes used for single-material plastics. Consequently, in countries with less regulation, like China, CFRP and FRP are frequently discarded in landfills or by incineration. However, the EU Management Committee and the United States Environmental Protection Agency (EPA) both started prohibiting the landfill disposal of CFRP materials in 2004, encouraging companies to start recycling (Chen et al., 2023).

4.5 Preparation of Samples

The Jute-Reinforced PLA Composite samples were prepared in-house for this investigation, as opposed to purchased materials (Material A and Material B). This decision was motivated by the practical constraints of limited resources and the need to assess whether less conventional materials would serve the purpose under study. In addition to these factors, the task was enhanced by the opportunity to observe and engage in the entire fabrication process.

Due to a scarcity of raw materials, the objective was to generate three 200mm x 200mm samples. After, the DeMec workshops machined all samples for the the tests that were carried out to determine the properties under study, including those that were not prepared (Material A and Material B).

Utilizing a hydraulic press, as seen in Figure 4.7 below, the preparation process was meticulously conducted at INEGI's facilities. However, the process was hampered by a defect in the press's cooling system, which unfortunately restricted the production capacity to only one sample per day.

The determination of optimal processing conditions was achieved through extensive experimentation, given the innovative nature of this study. The materials used in this process included jute fabric and PLA pellets, both illustrated in Figure 4.8. Initially, the press was set to a temperature of 170ºC and a pressure of 2.5 bar. Despite these settings, the PLA did not melt effectively, indicating the need for adjustments.

Consequently, the temperature was increased to 190ºC while maintaining the pressure at 2.5 bar. This adjustment led to a significant improvement, resulting in a robust connection between the PLA and the jute fabric. However, to ensure coherence and integrity of the composite material, each plate required exposure to two cycles of this process. This iterative approach was essential to achieve the desired mechanical properties and material consistency.

Figure 4.7: Press Machine Used for Sample Preparation.

(a) (b)

Figure 4.8: Raw Materials Used: (a) Jute Textile, (b) PLA Pellets.

The preparation of each sample involved the setup of three layers of jute fabric, with PLA pellets evenly dispersed between them (each layer of PLA was 350g), as depicted in the Figure 4.9 below. By employing this layering technique, the PLA effectively functioned as a binder, resulting in the formation of a consistent composite material. Although the cooling system was broken and required natural cooling, which resulted in a longer cycle time, the samples were still successfully produced, like the Figure 4.10 illustrates. The final three samples were machined to match the dimensions required for material property tests, ensuring their readiness for subsequent evaluation.

Figure 4.9: Layering Jute Fabric and PLA Pellets in the Mold.

The experiential method used for sample preparation provided significant knowledge on the process of composite manufacture and the real-world difficulties involved in dealing with biodegradable composites.

Figure 4.10: Final Jute-Reinforced PLA Composite Samples After Molding.

Firsthand knowledge of the various phases involved, including raw material selection and fabrication procedures, was acquired by actively participating in the sample preparation process. This interactive experience provided insight into the complexity of composite material manufacturing, encompassing aspects such as mixing proportions, molding techniques, and curing processes.

Figure 4.11: Some Machined Samples Ready for Testing.

4.6 Testing and Assessments

The subsequent phase, as outlined by Ashby (2011), involves the search for documentation pertaining to the candidates. This process entails thoroughly examining various elements of the selected materials until a comprehensive understanding is obtained, enabling a final decision to be reached. In order to provide an element of experimentation, this particular stage was modified into a testing phase, during which the three aforementioned materials undergo through evaluation in laboratory experiments. Documentation solicitations for the candidates inevitably occur as well.

4.6.1 Impact Resistance Test

The materials' impact resistance is assessed using the standard test technique specified in ASTM D7136/D7136M. This method evaluates the ability of the material to withstand damage caused by a drop-weight impact event. The experiment entails exposing a flat, rectangular composite plate (minimum dimensions of 100 mm x 150 mm). This test is achieved by utilizing a drop-weight setting equipped with a hemispherical impact tool. Before the test, the potential energy of the drop-weight is chosen by considering the mass and height from which the impact tool is dropped. The magnitude and nature of the damage in the specimen are measured in order to assess its resistance to harm. The damage resistance properties produced by this test method are influenced by various elements, such as specimen geometry, layup, impact tool geometry, and impact force, among others. It is crucial to acknowledge these influences (ASTM International, 2015).

In this case the tests were carried out using a Rosand falling weight impact tester, model Type 5hv (Figure 4.12), to evaluate the material's performance under sudden impact conditions. The testing specifications are as follows: Impact Energy: 10 Joules and Impact Tool Diameter: 16 mm.

Figure 4.12: Rosand Falling Weight Impact Tester, Type 5hv.

Initially, each composite sample was securely mounted on the impact tester's platform to ensure that it was positioned accurately under the impact tool. This was the start of the testing procedure. Following this, the impact tester was set up to generate an impact energy of 10 Joules, which corresponds to a pendulum height of 0.243 meters. These settings were selected due to a timing issue, as the machine was already configured with a pendulum and could only modify the energy setting. This is not pertinent, as it is still feasible to assess the energy absorbed by each material and, as a result, determine whether the material can withstand the fundamental requirement of withstanding "a concentrated perpendicular load of 2.0 kN applied over a symmetric area of not more than 0.01 m²." Following this, the machine's falling weight mechanism was activated, enabling the weight to descend from a predetermined height onto the sample. By measuring the energy absorbed by the material, the impact resistance of the sample was ultimately assessed. In addition to observations of any visible damage or deformation, this was documented.

It is crucial to highlight that two samples of the thickest material were subjected to testing using 5J and 10J setups to ensure that the results obtained would be coherent. Furthermore, in order to assess each material, three specimens were utilized in addition to this first setup test.

The objective of this test was to determine the material's ability to withstand a concentrated perpendicular load of 2.0 kN applied across a symmetrical area not exceeding 0.01 m², as specified by the certification requirements. The specimens utilized had dimensions of 100mm x 150mm and were subjected to testing using a 4kg pendulum with an energy of 10 joules. Consequently, calculations must be performed to determine if the material is capable of meeting the specified criteria.

4.6.2 Impedance Tube Sound Absorption Test

Finally, the sound absorption capabilities of the materials is assessed using the standardized test technique specified in ISO 10534-1. The procedure entails quantifying the sound absorption coefficient of materials by the utilization of the impedance tube method. The ISO 10534-1 standard outlines a method for measuring the sound absorption coefficient and impedance of materials using an impedance tube.

Considering the time constraints of this project, it is practical and effective to prioritize the absorption coefficient of all acoustic testing. This is because it directly affects passenger comfort by altering airborne noise, echoes, and reverberations in train cabins. Absorptive materials offer improvements to the acoustic environment without the need for substantial structural modifications. This study establishes a strong basis for future investigations on isolation and dampening, guaranteeing a thorough approach to acoustic enhancement in train interiors.

For this test, a specimen of the material, trimmed to match the dimensions of the impedance tube (in this instance, with diameters of 29 mm and 100 mm), is inserted into each tube. Sound waves are produced and directed towards the material. The sound pressure levels are measured by two microphones positioned at separate points within the tube. The data obtained from the microphones is processed in order to calculate the sound absorption coefficient of the material (International Organization for Standardization, 2001).

The values obtained are for waves that are transmitted perpendicular to the material and the measurements are made using octave band. Subsequently, an empirical formulation is then created to suit a diffuse wave field. In this case there is no preferential sample face, so the positioning side of the sample is meaningless.

The 1/3 octave band would have been equally appropriate and even more precise; however, due to time constraints and sample limitations, it was determined to conduct the tests exclusively with the octave band.

ISO 10534-1 has been withdrawn and replaced by a new version, which is of significant importance to acknowledge. Nevertheless, the previous ISO standard is still being adhered to in this particular situation due to the limitations present in the laboratories and the fact that the tests are still being conducted under comparable circumstances. The impedance tube, equipped with a sound source connected to one end, is still utilized, with only the measuring technique being different.

Figure 4.13: General Layout of the Impedance Tube Sound Absorption Test.

4.6.3 Other Assessments

Considering the project's scope, each material is under evaluation in terms of Life Cycle Assessment (LCA). Conducting comprehensive LCA studies needs the allocation of diverse resources, including financial and time. Consequently, in this case it is imperative to simplify certain aspects of the study in practical application. According to ISO 14040 (International Organization for Standardization, 2006), the study begins by establishing the purpose and scope of the analysis. This is followed by conducting an inventory, assessing the environmental impacts, and concluding with the interpretation of the results. It is also crucial to acknowledge that the company that provided the samples has already conducted LCA studies on Material B and Material A. Therefore, the LCA for the Jute-Reinforced PLA composite was tailored specifically for this study. This approach adheres to the principles and framework outlined in ISO 14040, however, the analysis had to be streamlined due to the unavailability of tools and because it was not the primary topic of this thesis.

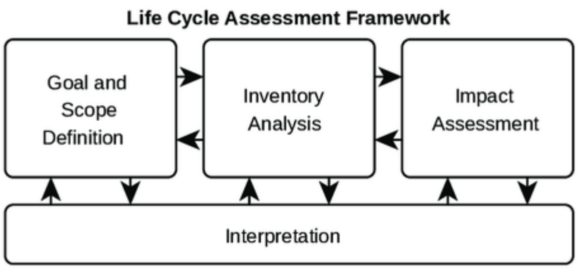


Figure 4.14: Steps of LCA According to ISO 14040 (Tornaghi et al., 2018).

In addition to the LCA, a cost analysis will be conducted to compare the prices of each material.

4.7 Results

This section presents the results of the tests and assessments. Prior to that, the following table 4.1 provides a summary of the materials that are now being investigated, as well as their respective weights for a 100mm x 100mm sample.

Table 4.1: Materials Under Study and Their Weights.

Materials	Material A	Material B	Jute + PLA
Weight (g)	62	59	26

4.7.1 Impact Resistance

The results of the impact testing are displayed below, as well as the calculations to evaluate if the goal of determining if the material had the ability to withstand a concentrated perpendicular load of 2.0 kN applied across area not exceeding 0.01 m² was achieved or not.

The tables provided represent the mean values of all the samples for each material, as each material underwent testing on three separate samples and featuring an offset of 110 N. The graph represents the comparison between Force vs. Time Analysis of the three materials.

Load Goal

The goal is to withstand a load of 2.0 kN over an area of not more than 0.01 m².

$$\sigma_{\text{specified}} = \frac{2000\ \text{N}}{0.01\ \text{m}^2} = 200000\ \text{Pa} = 200\ \text{kPa} \quad (4.1)$$

Jute + PLA composite

Table 4.2: Results for Impact Test for Jute+PLA Composite.

Test Results				
	Values at Peak		**Values at Failure**	
Force [N]	**Distance [mm]**	**Energy [J]**	**Distance [mm]**	**Energy [J]**
222.66	**4.33**	**0.45**	**10.22**	**1.39**

Calculation at Peak

The force handled by the sample during testing was 222.655 N over the sample area (100 mm × 150 mm = 0.015 m²).

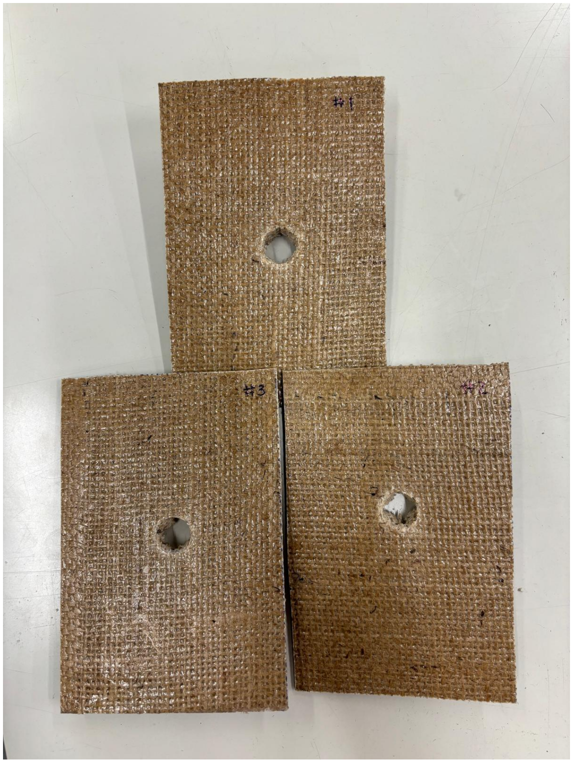


Figure 4.15: Jute + PLA Samples after Impact Test.

$$\sigma_{\text{peak}} = \frac{222.66 \text{ N}}{0.015 \text{ m}^2} = 14844 \text{ Pa} = 14.84 \text{ kPa} \tag{4.2}$$

The material samples did not withstand the specified concentrated load of 2.0 kN over an area of 0.01 m². The samples were destroyed under much lower forces and energies, indicating that the material is not suitable for the specified load condition.

Material A

Table 4.3: Results for Impact Test for Material A.

Test Results				
	Values at Peak		**Values at Failure**	
Force [N]	**Distance [mm]**	**Energy [J]**	**Distance [mm]**	**Energy [J]**
1565.1	**1.79**	**1.44**	**10.26**	**7.47**

Calculation at Peak

The force handled by the sample during testing was 1565.1 N over the sample area (100 mm $\times$ 150 mm = 0.015 m^2).

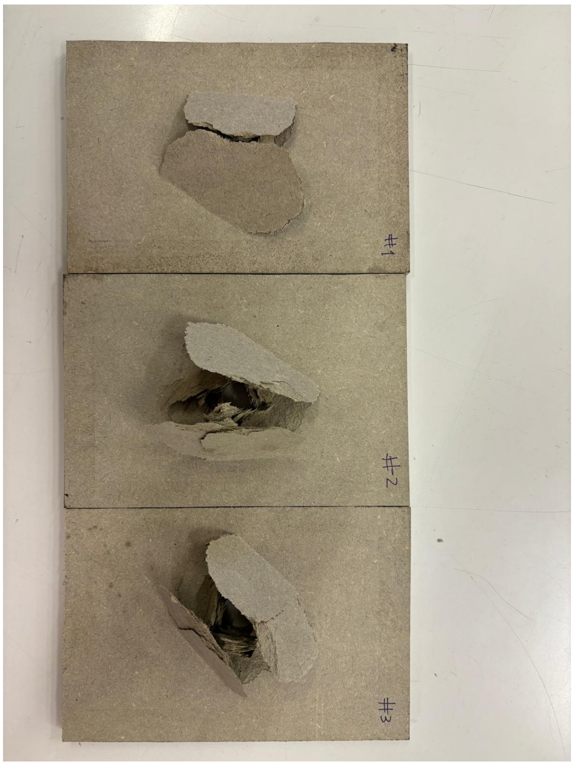


Figure 4.16: Material A Samples after Impact Test.

$$\sigma_{\text{peak}} = \frac{1565.1\,\text{N}}{0.015\,\text{m}^2} = 104340\,\text{Pa} = 104.34\,\text{kPa} \tag{4.3}$$

The material samples did not withstand the specified concentrated load of 2.0 kN over an area of 0.01 m^2. The samples were destroyed under lower forces and energies, indicating that the material is not suitable for the specified load condition.

Material B

Table 4.4: Results for Impact Test for Material B.

Test Results				
	Values at Peak		**Values at Failure**	
Force [N]	**Distance [mm]**	**Energy [J]**	**Distance [mm]**	**Energy [J]**
700.52	**2.99**	**1.09**	**10.83**	**5.27**

Calculation at Peak

The force handled by the sample during testing was 700.517 N over the sample area (100 mm $\times$ 150 mm = 0.015 m^2).

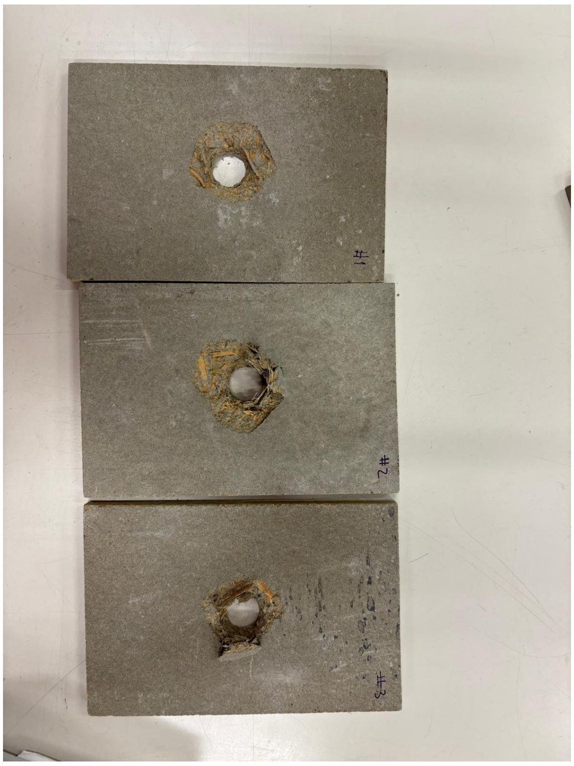


Figure 4.17: Material B Samples after Impact Test.

$$\sigma_{\text{peak}} = \frac{700.52\,\text{N}}{0.015\,\text{m}^2} = 46701.33\,\text{Pa} = 46.70\,\text{kPa} \tag{4.4}$$

The material samples did not withstand the specified concentrated load of 2.0 kN over an area of 0.01 m^2. The samples were destroyed under lower forces and energies, indicating that the material is not suitable for the specified load condition.

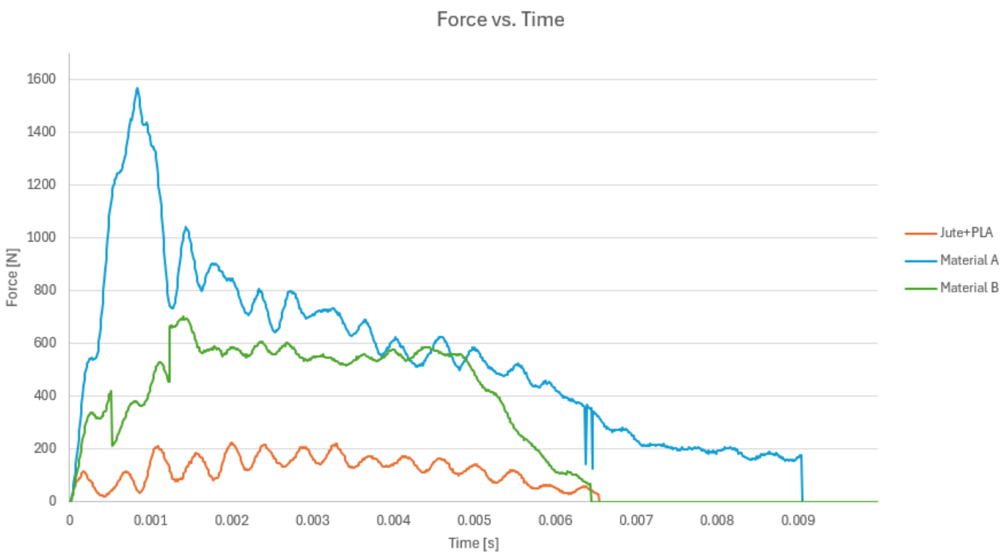


Figure 4.18: Results of Force Vs. Time of the three materials.

It is important to note that, since none of the materials satisfy the impact requirement, it does not imply that increasing thickness of each material won't make the outcome better.

4.7.2 Sound Absorption

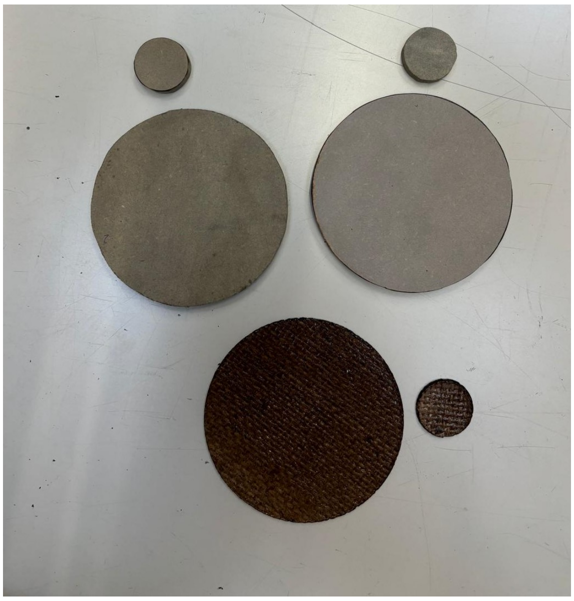


Figure 4.19: Sound Samples Used.

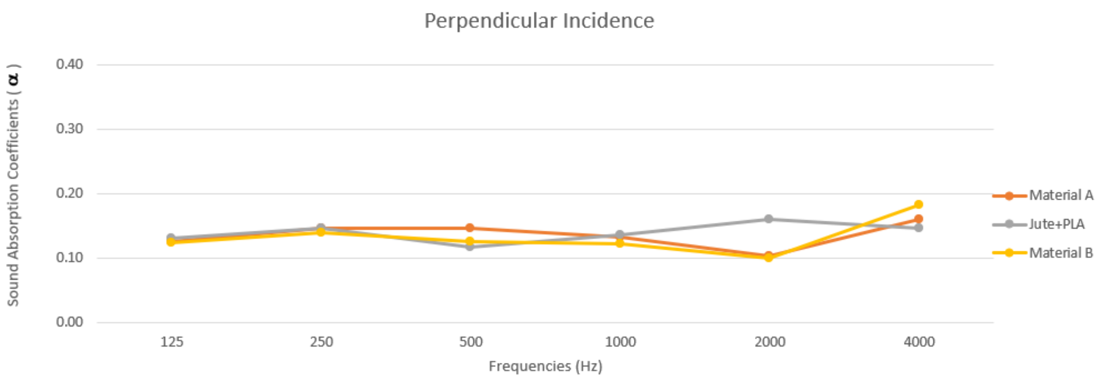
The results of the stationary wave tube test are summarized below in Table 4.5. Results of the sound absorption coefficient acquired directly by the tube for a normal incidence of sound waves are presented in the first column of the table. The values obtained by the system for the extrapolation of a random incidence of waves are represented in the subsequent column.

It is crucial to emphasize that in order to obtain more accurate results for random incidence, an experiment should be conducted in a reverberant chamber with $10m^2$ samples.

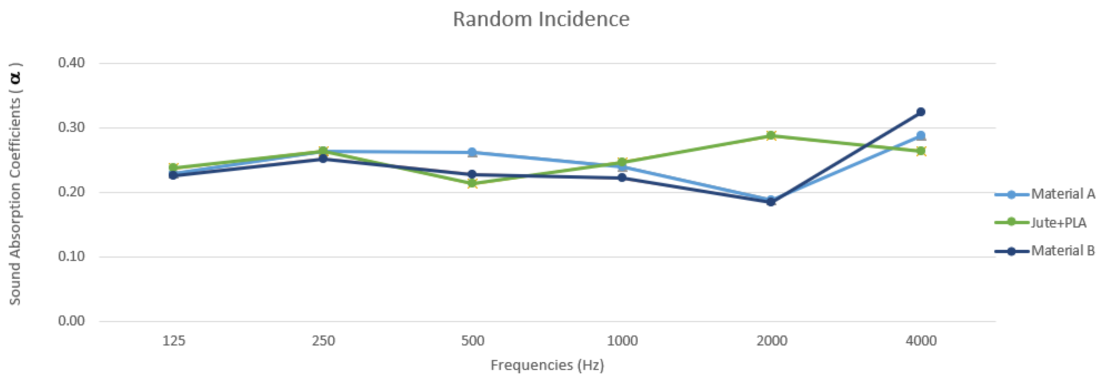
Additionally, below the table, there are graphs that facilitate the visual comparison of the findings obtained from the different materials.

Table 4.5: Sound Absorption Coefficients For Each Frequency.

Sound Absorption Coefficients (α)						
	Perpendicular Incidence			**Random Incidence**		
Freq. (Hz)	Material A	Jute+PLA	Material B	Material A	Jute+PLA	Material B
125	0.13	0.13	0.12	0.23	0.24	0.23
250	0.15	0.15	0.14	0.26	0.26	0.25
500	0.15	0.12	0.13	0.26	0.21	0.23
1000	0.13	0.14	0.12	0.24	0.25	0.22
2000	0.10	0.16	0.10	0.19	0.29	0.18
4000	0.16	0.15	0.18	0.29	0.26	0.32



(a)



(b)

Figure 4.20: Comparison of absorption coefficients between materials: (a) Perpendicular Incidence, (b) Random Incidence.

The sound absorption properties of all the materials are mediocre. This does not imply that the combination of the materials under investigation with a sponge-like material won't produce more favorable outcomes.

Additionally, upon comparing the three materials, it is evident that they exhibit identical behavior at all frequencies, with the exception of 2000Hz, where the Jute+PLA composite differentiates itself marginally. The results tend to improve slightly with the increase of frequency.

4.7.3 LCA

The objective of this Life Cycle Assessment (LCA) is to assess the environmental effects of utilizing Jute-Reinforced PLA Composite as panel material for railway carriages.

The product system of Jute-Reinforced PLA composite panels is included in the scope, with a functional unit of one cubic meter (m^3) of the composite panel. The LCA encompasses the following stages: extraction and production of raw materials, manufacturing of the composite panels by compression molding; use phase in the railway system and end-of-life possibilities. This study does not consider the effects associated with the infrastructure, maintenance, and auxiliary services. Furthermore, the lack of adequate data prevents the consideration of transportation steps.

Below is the inventory of supplies for each phase of the system under investigation.

- **Extraction and manufacturing of raw materials:**

  PLA pellets: PLA pellets are small cylinders that consist of PLA Luminy LX175. PLA (polylactic acid) is a biodegradable plastic that is derived from natural resources, including starch extracted from maize, sugar beet root, and wheat. Given the sample dimensions of 20 cm $\times$ 20 cm $\times$ 3 mm and a mass of 700 g, it is necessary to determine the mass of PLA pellets needed for a functional unit of 1 cubic meter.

$$\text{Length} = 20\text{ cm} = 20\times10^{-2}\text{ m} = 0.2\text{ m} \tag{4.5}$$

$$\text{Width} = 20\text{ cm} = 20\times10^{-2}\text{ m} = 0.2\text{ m} \tag{4.6}$$

$$\text{Height} = 3\text{ mm} = 3\times10^{-3}\text{ m} = 0.003\text{ m} \tag{4.7}$$

$$V_{\text{sample}} = \text{Length}\times\text{Width}\times\text{Height} = 0.2\text{ m}\times0.2\text{ m}\times0.003\text{ m} = 1.2\times10^{-4}\text{ m}^3 \tag{4.8}$$

Mass used in the sample

$$m_{\text{sample}} = 700\text{ g} = 700\times10^{-3}\text{ kg} = 0.7\text{ kg} \tag{4.9}$$

Mass of PLA pellets required for 1 cubic meter

$$\frac{m_{\text{sample}}}{V_{\text{sample}}} = \frac{0.7\text{ kg}}{1.2\times10^{-4}\text{ m}^3} = 5833.33\text{ kg/m}^3 \tag{4.10}$$

Therefore, the mass of PLA pellets required for a functional unit of 1 m^3 is 5833.33 kg.

Jute Fabric: jute is a naturally occurring fiber that is obtained and processed from jute plants. The energy consumption of natural fibers is comparatively lower than that of synthetic fibers, although it does require agricultural inputs. The emissions are negligible, predominantly associated with agricultural machines. After being separated, the fibers undergo a series of steps including washing, drying, grading, and are subsequently transported to jute mills for further processing into jute yarn. It is biologically degradable, with multipurpose usage, without any coating.

Given the sample dimensions of 20 cm × 20 cm × 3 mm and the use of 3 layers of jute fabric, the path is to estimate the quantity of jute used in each sample and extrapolate it to a functional unit of 1 cubic meter. The weight of the jute fabric is given as 320 g/m^2. Textiles, being typically thin, are often described by their weight per square meter rather than their density.

Area of one layer of jute fabric

$$\text{Length} = 20\text{ cm} = 20 \times 10^{-2}\text{ m} = 0.2\text{ m} \tag{4.11}$$

$$\text{Width} = 20\text{ cm} = 20 \times 10^{-2}\text{ m} = 0.2\text{ m} \tag{4.12}$$

$$A_{\text{layer}} = 0.2\text{ m} \times 0.2\text{ m} = 0.04\text{ m}^2 \tag{4.13}$$

Total area of jute fabric

$$A_{\text{total}} = 3 \times A_{\text{layer}} = 3 \times 0.04\text{ m}^2 = 0.12\text{ m}^2 \tag{4.14}$$

Mass of jute fabric in one sample

Given the weight of jute fabric m_{jute} is 320 g/m^2.

$$m_{\text{sample}} = m_{\text{jute}} \times A_{\text{total}} = 320\text{ g/m}^2 \times 0.12\text{ m}^2 = 38.4\text{ g} \tag{4.15}$$

Mass of jute fabric for 1 cubic meter

The total mass of the composite for the functional unit of 1 cubic meter is 5833.33 kg, and the mass of the PLA in the composite is 5833.33 kg.

Volume of one sample:

$$V_{\text{sample}} = 0.2\ \text{m} \times 0.2\ \text{m} \times 0.003\ \text{m} = 1.2 \times 10^{-4}\ \text{m}^3 \tag{4.16}$$

Number of samples per cubic meter:

$$n = \frac{1\ \text{m}^3}{1.2 \times 10^{-4}\ \text{m}^3} = \frac{1}{1.2 \times 10^{-4}} \approx 8333.33 \tag{4.17}$$

Total mass of jute for 1 cubic meter:

$$m_{\text{jute, 1 m}^3} = n \times m_{\text{jute}} = 8333.33 \times 38.4\ \text{g} = 320000\ \text{g} = 320\ \text{kg} \tag{4.18}$$

Therefore, the mass of jute fabric required for a functional unit of 1 m^3 is 320 kg.

- **Production:**

  Compression molding is used to create composite panels by mixing PLA pellets and jute layers and subjecting them to pressure. Substantial energy consumption occurs as a result of the heating and pressure exerted during the molding process. The amount of waste generated is limited, as the majority of the material is effectively employed in the construction of the panel.

  The produced panels undergo machining to precisely match any specific measurements. The energy consumption of the machinery used in molding is significantly higher than that of the machinery used in this process, mostly due to the electrical usage. The machining waste consists mostly of dust and small off-cuts.

  The average energy consumption of these Hydraulic Press Machines is around 1.2 kWh. Besides energy, a polytetrafluoroethylene (PTFE/Teflon) film is used to prevent the composite from adhering to the mold during the high-temperature process. For a 1 m^3 model, the quantity of PTFE film required is around 2,18 g (supplier value).

- **Usage:**

  As a result of limited time and resources, there is currently no prediction model available to evaluate the lifespan of the constructed composite.

The installation of these panels occurs within trains. Lightweight panels help reduce energy consumption in train operations. The expected lifespan of the panels is around 10 to 15 years, without the need for maintenance, due to their robustness and minimal upkeep demands.

- **End of Life:**

  As a result of limited time and resources, there is currently no predictive model available to determine the longevity of the constructed composite.

  When natural fibers and bio-polymer matrix (like PLA) are combined, both components come from renewable sources, and these bio-composites have the potential to be biodegradable. In addition to bio-degradation, the recycling of bio-composites enhances their appeal by prolonging their life cycle and minimizing their global environmental effect through reduced raw material use and long-term carbon preservation.

- **Comparison**

  The Life Cycle Assessments (LCAs) allow for a comparison based on a uniform functional unit of one cubic meter. These assessments cover different environmental effect categories, including energy consumption and greenhouse gas emissions. However, they do not take into account end-of-life situations and merely assume that the garbage will be disposed of in regular municipal construction waste containers.

  The analysis of these materials indicates that Jute-Reinforced PLA composite panels offer significant environmental advantages, especially when considering their end-of-life implications. The combination of natural fibers and a bio-polymer matrix (PLA) in composite panels offers a sustainable alternative to conventional materials, due to the biodegradability potential of the natural fibers. This component is crucial because it promotes long-term environmental conservation and resource efficiency by decreasing the usage of raw materials and retaining carbon.

4.7.4 Cost Analysis

Performing a cost analysis is an essential stage in making informed decisions regarding the choice of materials for the interior panels of railway carriages. This approach aids in achieving an optimal balance between green credentials and economic viability. With this in mind, the following analysis allows to compare the three tested material as well as a material commonly used in railway interior panels.

It is significant to highlight that the costs for the Jute-Reinforced PLA composite are estimated using the market prices of its raw components, whereas the cost numbers for Material B, Material A and PC are based on confidential data provided by suppliers.

The Kenaf+PLA composite's CES EduPack 2024 values were employed for this cost analysis due to their close similarity in market prices to Jute+PLA composites (and the absence of price information for Jute+PLA composite). When combined with PLA, both Kenaf and Jute are natural fibers that exhibit comparable performance characteristics and applications. Furthermore, Kenaf is generally slightly more expensive than Jute, which offers a conservative estimate of the cost. The integrity and reliability of the financial assessment are maintained by ensuring that the final cost calculations are not underestimated and a reliable approximation is obtained by utilizing these values.

Given Data

- Price per kg (Kenaf + PLA composite): 2.8 €/kg to 3.26 €/kg
- Weight of 100mm x 100mm x 3mm sample (Jute + PLA composite): 26 g
- Area of 100mm x 100mm sample: $0.01\,\text{m}^2$

Calculations

Weight per Unit Area for 3mm Sample

$$\text{Weight per unit area for 3mm sample} = \frac{26\,\text{g}}{0.01\,\text{m}^2} = 2600\,\text{g/m}^2 = 2.6\,\text{kg/m}^2 \tag{4.19}$$

Average Price per Kilogram

$$\text{Average price per kg} = \frac{2.8\,\text{€/kg} + 3.26\,\text{€/kg}}{2} = 3.03\,\text{€/kg} \tag{4.20}$$

Price per Unit Area for 3mm Sample

$$\text{Price per unit area} = \text{Weight per unit area for 3mm sample} \times \text{Average price per kg} \tag{4.21}$$

$$\text{Price per unit area for 3mm sample} = 2.6\,\text{kg/m}^2 \times 3.03\,\text{€/kg} = 7.878\,\text{€/m}^2 \tag{4.22}$$

Assuming manufacturing cost as zero and considering that the final price will always be a slightly higher value than what is given here due to direct labor cost and manufacturing overhead, the price per square meter is 7.9 €. It's crucial to remember that the materials differ in thickness; therefore, if the jute+pla thickness was increased, the cost would be more in line with Materials A and B.

Estimated Weight per Unit Area for 8mm Sample

$$\text{Weight per unit area (8mm sample)} = \frac{8\,\text{mm}}{3\,\text{mm}} \times 2.6\,\text{kg/m}^2 = \frac{8}{3} \times 2.6\,\text{kg/m}^2 = 6.9333\,\text{kg/m}^2 \tag{4.23}$$

Estimated Price per Unit Area

$$\text{Price per unit area} = \text{Weight per unit area for 8mm sample} \times \text{Average price per kg} \tag{4.24}$$

$$\text{Estimated Price per Unit Area for 8mm Sample} = 6.93\,\text{kg/m}^2 \times 3.03\,\text{€/kg} = 21.01\,\text{€/m}^2 \tag{4.25}$$

Presented below is the table 4.6 that provides a comparison between all prices.

Table 4.6: Comparison of Minimum Prices Between Materials.

	Material B	Material A Fire Proof	Jute + PLA
Price €/m²	10.30€	19.60€	7.90€

Jute + Pla composite is the least expensive material. It is important to mention that these are the costs for the minimum thicknesses specified by the manufacturer of Material A and Material B (8 mm) and for the thickness used in the production of the Jute+PLA composite (3 mm). Consequently, it is a comparison of the minimum prices for the three materials.

4.8 Selection

4.8.1 Calculation of Candidates' Index

Ashby's method is highly regarded for its efficiency and simplicity. It involves the derivation of material indices from fundamental performance equations, enabling the identification of optimal materials based on specific performance metrics. The performance index P in Ashby's method is typically expressed as:

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M) \tag{4.26}$$

where $f_1(F)$, $f_2(G)$, and $f_3(M)$ represent separate functions related to functional requirements, geometrical requirements, and material properties, respectively. This approach allows for the simplification of the material selection process, focusing primarily on one objective usually minimizing mass or price.

However, in scenarios involving multiple criteria with varying units and scales, a different approach may be more suitable. To address this, one of the methods proposed by Hwang and Yoon (1981) was adopted, the Simple Additive Weighting (SAW). This approach provides a systematic way to handle multiple criteria by normalizing and weighting them, thus facilitating a comparison and selection process. It can be used when the assumption of preference independence[2]and preference separability[3] are met, which is the case.

Although there is a wide range of Multi-Criteria Decision Making (MCDM) methods, several studies, such as Athawale and Chakraborty (2012), has provided valuable insights into how different strategies perform in comparison to each other. Although Simple Additive Weighting (SAW) is not commonly recognized as the ultimate best method, it has shown good effectiveness in comparative assessments. The performance of this strategy alongside its simplicity and ease to understand, compared to many other options, highlights its importance and usefulness in selecting materials.

In this case, the performance index (PI) that uses the Simple Additive Weighting (SAW) method to combine criteria using a weighted approach is defined as follows:

$$PI = w_S \cdot \frac{S}{S_{\max}} + w_I \cdot \frac{I}{I_{\max}} + w_C \cdot \frac{C_{\min}}{C} + w_W \cdot \frac{W_{\min}}{W} \tag{4.27}$$

Where:

- S: Sound absorption coefficient.
- I: Impact Force Handled.
- C: Cost per square meter.
- W: Weight of a 100mm x 100mm sample.

The weights $(w_F, w_S, w_I, w_C, w_W)$ are assigned based on the importance of each criterion. Weights indicate the relative significance of each criterion in the process of reaching a choice. Decision-makers are able to assign higher importance to particular traits compared to others, depending on the specific requirements and objectives of the application. The total of all weights must be equal to 1 (or 100%).

In this case, the selected weights demonstrate a well-rounded approach that gives priority to safety considerations and weight (because of the implications it has regarding the energy consumption of the vehicle), while also taking into account other crucial elements like as sound absorption, cost, and weight. The weights were set by considering stakeholder feedback, regulatory compliance, judgment, cost-benefit assessment, and alignment with project objectives. Assuming weights:

- Sound Absorption: $w_S = 0.2$

[2]Preference independence suggests that a decision-maker's preferences regarding different attributes or options are independent of each other. In other words, how much a decision-maker prefers one option over another in one aspect should not influence their preference between those options in another aspect. It's often represented mathematically through utility functions that are additive across dimensions Keeney and Raiffa (1976).

[3]Preference separability, as introduced by Gorman Gorman (1968), suggests that the preferences for different goods or attributes can be analyzed separately. This means that the overall utility a person derives from a combination of goods can be understood by considering the individual utilities of each good separately.

- Impact Resistance: $w_I = 0.3$
- Cost: $w_C = 0.2$
- Weight: $w_W = 0.3$

Normalization is the procedure of converting several units and scales of criteria into a standardized scale, usually ranging from 0 to 1. This enables a fair and impartial comparison across criteria that may initially have significantly different ranges or units. The values for each criterion are normalized by comparing them to the highest or lowest values found across all materials. Costs that are less expensive are preferable. Therefore, we normalize by utilizing the minimum value in the denominator to guarantee that improved performance results in higher normalized values. The normalization equations, which have already been integrated into the previously stated general performance index equation, are provided below.

Normalized Value for Maximization:

$$\text{Normalized Value for Maximization} = \frac{\text{Actual Value}}{\text{Maximum Value}} \tag{4.28}$$

Normalized Value for Minimization:

$$\text{Normalized Value for Minimization} = \frac{\text{Minimum Value}}{\text{Actual Value}} \tag{4.29}$$

Where:

- **Actual Value**: The actual value of the criterion for a particular material.
- **Maximum Value**: The maximum value of the criteria observed among all materials (for maximization).
- **Minimum Value**: The minimum value of the criteria observed among all materials (for minimization).

Given the properties we are utilizing in this particular case, the following are the pertinent factors for normalization.

$$S_{\text{max}} = 0.14, \quad I_{\text{max}} = 104.34, \quad C_{\text{min}} = 7.9, \quad W_{\text{min}} = 26$$

In the case of Sound absorption coefficient, given the acoustic properties of train interior wall panels, the frequency of 1000 Hz was selected for the purpose of developing the material index. Railway noise is primarily produced in the lower to mid-frequency ranges (100 Hz to 1000 Hz) by aerodynamic effects, engines, and wheels. Consequently, this selection depends on this fact. The human hearing is particularly susceptible to noise in the mid-range frequencies, rendering 1000 Hz an important limit for noise reduction initiatives aimed at improving passenger comfort.

Below the index for each material is calculated accordingly to Equation 4.27.

Material Index Calculation for Jute + PLA

$$M_{\text{jute}} = 0.2 \cdot \left(\frac{0.14}{0.14}\right) + 0.3 \cdot \left(\frac{14.84}{104.34}\right) + 0.2 \cdot \left(\frac{7.9}{7.9}\right) + 0.3 \cdot \left(\frac{26}{26}\right) \qquad = 0.74 \tag{4.30}$$

Material Index Calculation for Material A

$$M_{\text{Material A}} = 0.2 \cdot \left(\frac{0.13}{0.14}\right) + 0.3 \cdot \left(\frac{104.34}{104.34}\right) + 0.2 \cdot \left(\frac{7.9}{19.6}\right) + 0.3 \cdot \left(\frac{26}{62}\right) \qquad = 0.69 \tag{4.31}$$

Material Index Calculation for Material B

$$M_{\text{Material B}} = 0.2 \cdot \left(\frac{0.12}{0.14}\right) + 0.3 \cdot \left(\frac{46.7}{104.34}\right) + 0.2 \cdot \left(\frac{7.9}{10.3}\right) + 0.3 \cdot \left(\frac{26}{59}\right) \qquad = 0.59 \tag{4.32}$$

Index Comparison

The material indices for the three materials are as follows:

$$\begin{aligned} M_{\text{jute}} &= 0.74 \\ M_{\text{Material A}} &= 0.69 \\ M_{\text{Material B}} &= 0.59 \end{aligned}$$

Based on these calculations, Jute + PLA composite has the highest material index, indicating it is the best choice among the three materials when considering the weighted factors of sound absorption, impact resistance, cost, and weight.

Naturally, none of these materials meet the requirements set forth by the railways, but the composite made of PLA and jute has a very high potential for further research because of its higher index.

It is crucial to emphasize that this index is based on various variables. If a factor is to be prioritized for another study, the selection must be modified to align with the newly determined requirements of the project.

Chapter 5

Conclusions

5.1 Objective Satisfaction

The study began with a thorough analysis of the present condition of the Portuguese railway sector. By conducting a thorough analysis that considered the virtues, drawbacks, prospects, and obstacles, we obtained significant insights into the social accountability landscape of the industry. Although this study laid a strong groundwork, it is recognized that future research could enhance the analysis by incorporating a wider array of issues and stakeholders, leading to a more intricate comprehension of the industry's social responsibility procedures.

The main objective of the research was to suggest a framework specifically designed to prioritize social responsibility in terms of environmental, economic, and social aspects within the Portuguese railway sector. The issue in question was answered.

An essential element of the research entailed creating a case study to demonstrate the execution of the previous addressed framework. More precisely, the objective was to investigate environmentally sustainable options for train interior wall panels, evaluating their cost and other characteristics. The case study failed to showcase the viability of implementing sustainable materials in the railway infrastructure. Nevertheless, since the case study had a restricted scope, doing further investigations encompassing a broader array of materials and scenarios will yield a more exhaustive comprehension, possibly bringing potential new approaches.

Regarding Sustainable Development Goals (SDGs), the researches' focus on testing unconventional materials contributes to the support of *SDG 9: Industry, Innovation, and Infrastructure*, particularly in stimulating innovation within the railway sector. The research further supports *SDG 13: Climate Action* by investigating materials that have the potential to decrease the environmental consequences of railway infrastructure. In addition, the survey to assess the perception of various stakeholders, specifically focuses on *SDG 11: Sustainable Cities and Communities*. This part guarantees that the solutions created take into account the requirements and viewpoints of the population, consequently helping to the creation of more inclusive and strong communities. The project's dedication to social responsibility aligns with *SDG 10: Reduced Inequalities*, as it guarantees that the advantages of sustainable practices are available to a wide range of stakeholders, including marginalized communities such as the interior of Portugal or districts lacking access to railways.

In summary, the research has achieved significant efforts to improve social responsibility in the Portuguese railway sector. Nevertheless, it is acknowledged that additional research is required to expand these preliminary discoveries and guarantee their enduring viability and influence.

5.2 Limitations of the Present Study

It is crucial to recognize certain limitations that could impact the applicability of this Thesis' results.

A major constraint of this study is the small sample size and its representation. Despite attempts to collect data from a wide variety of participants for the surveys and interviews, the sample may not accurately reflect the complete population of railway passengers and stakeholders in Portugal. This has the potential to result in biases in the statistics, as specific demographic groups or user categories may be inadequately represented.

In addition, the case study examines the substitution of interior panels with environmentally friendly materials and offers significant insights. However, it only addresses a certain area operations. Although not covered in this study, other factors such as energy consumption, maintenance methods, and customer service also significantly contribute to the overall social responsibility of the railway system.

It remains crucial to recognize that given the results obtained in the acoustic and impact tests, it was decided not to proceed with the fire and smoke tests due to their high cost. However, by changing the direction of the research, and therefore probably improving the results of the tests mentioned above, it might be interesting to finally carry out the fire and smoke test.

In addition, the data analysis tools utilized, such as hypothesis testing using SPSS and descriptive statistics with Excel, have inherent limitations. Hypothesis tests, such as the T-Test and One Sample Binomial Test, are valuable tools. However, it is important to note that these tests are influenced by both the size of the sample and the assumptions made about the distribution of the data. Furthermore, the examination of open-ended survey replies, while providing valuable insights, is susceptible to interpretive biases.

The investigation was limited in scope due to financial and resource restrictions. The research was limited in its scope and extent due to constraints in funding, availability of testing materials, and access to advanced analytical methods. As a result, several lines of investigation with potential value were unable to be pursued.

The selection of Material B, Material A, and Jute-Reinforced PLA Composite as materials for examination in the case study was made considering their perceived ecological advantages, mechanical characteristics, and accessibility from suppliers. Material B and Material A are renowned for their exceptional durability and pleasing aesthetic attributes, whereas Jute-Reinforced PLA Composite provides distinct advantages in terms of its biodegradability. However, the selection of these materials was based on search criteria and their availability for sample, and so it does not encompass the entire range of sustainable and innovative materials that are now accessible.

Finally, it is important to recognize that the Life Cycle Assessment (LCA) conducted for each material has various inherent constraints. Firstly, it lacks information about the local effects. In addition, the study exclusively examines environmental factors, disregarding the social and economic consequences that are as crucial for a thorough assessment of sustainability. The choices and assumptions made in the LCA can be subjective, which may introduce bias into the results.

5.3 Concluding Remarks

The study began by conducting a thorough investigation of the Portuguese railway sector, which provided valuable information about its social responsibility framework. The main objective was to create a model that prioritizes social responsibility in terms of environmental, economic, and social aspects. The proposed approach exhibited potential and scalability, although needing real-world validation and participation with a wider range of stakeholders to guarantee sustained success.

The survey was conducted to establish conclusions and patterns. It was possible to deduce that the majority of railway users are under the age of 40 and that there is a lack of awareness regarding promotional campaigns and special initiatives. In terms of suggestions and demands, a significant number of respondents advocate for the inclusion of railways in every district, emphasizing the significance of network expansion and connectivity. This was evident in both the open-ended responses and the responses that were explicitly related to the subject matter.

The majority of passengers earn less than 2000 €, which is likely due to the fact that young people use the service more and therefore earn less. However, this is not the only factor that influences it.

It was possible to assess a generally positive attitude towards social responsibility activities, although this was not as important as worries about expanding the network or setting ticket prices.

Certain stakeholders have expressed concerns about the current state of Portuguese railways in terms of reliability, efficiency, and prices. These observations underscore the importance of effective communication and collaboration in order to resolve the current issues and establish consensus to facilitate enhancements. Particularly because it was feasible to evaluate a substantial negative correlation with passengers' prior negative experiences.

The case study examining sustainable materials for train interiors has verified the practicality of integrating environmentally friendly solutions. The material tests revealed several significant findings, including the fact that none of the candidates is suitable for integration into the railway industry, at least under the conditions that were established for this study. In terms of impact, all materials were unsuccessful; however, the composite made for this study, the Jute + PLA, achieved the most favorable outcome with the highest index.

The cost analysis emphasized the economic impact of implementing sustainable materials, however additional research is required to enhance the precision of the evaluation. The use of minimum values for each material in the cost analysis, as opposed to using the price for all equal thicknesses, significantly alters the values. However, this approach leads to inquiries about the necessity of achieving the thickness of material A and B in order to achieve equivalent or better characteristics.

While the index suggests that Jute + PLA is more suitable for this application, there is potential for both researching additional solutions and making improvements to the existing ones. For instance, enhancing thickness or incorporating other materials may improve their attributes.

Lastly, it is important to acknowledge that the potential for railroad application is still present, despite the fact that none of the candidates under study is suitable for this purpose. The challenge is to conduct more comprehensive and diverse studies with fewer time constraints.

5.4 Future Work

Given the knowledge and conclusions obtained from this study, it is imperative to conduct future investigations in various areas to enhance the understanding and application of sustainable materials in the railway industry.

To ensure the proposed model is validated and improved, it is essential for the Portuguese Railways to engage with a wider range of stakeholders, including their costumers. In addition, investigating novel re-purposing techniques for materials utilized in railway infrastructure might further augment sustainability, for example to assess a second life cycle stage for the panels (for instance decoration or grinding re-purpose for items with low mechanical requirements).

Future research should also focus on evaluating the compatibility and performance of integrating the tested materials with porous materials to improve their acoustic and impact resistance characteristics.

Within the field of acoustics, it would be valuable to perform thorough examinations of additional acoustic characteristics in order to obtain a comprehension of the materials' ability to insulate sound and vibrations. Although it would also be important to assess other mechanical properties like thermal inertia or fatigue resistance.

In addition, it would be beneficial to investigate the impact of increasing the thickness of materials on their mechanical, acoustic, and fire resistance characteristics in order to identify the most suitable arrangements. The setting of sandwich structure or the increase of fiber weight percentage in the composite are also very intriguing to look into, in this context.

The testing of composites using textile production leftovers would also be intriguing to address in the context of railways, as the primary concern is social responsibility, and the present study was hampered by a lack of time and a malfunctioning molding machine.

For the Life Cycle Assessment, it would be helpful to employ specialist software to accurately measure the environmental impacts of the suggested materials over their entire lifespan.

Long-term studies are essential for monitoring the impact and effectiveness of sustainable practices that have been implemented. These studies are vital to ensure ongoing improvement and adaptability to changing environmental regulations and industrial requirements. Additional research could explore the potential for partnering with foreign railway operators to gain useful insights and promote the sharing of best practices.

By focusing on these specific areas, future research can make valuable contributions to the advancement of a more sustainable and socially conscious railway sector. This, in turn, will result in enhanced environmental performance, economic feasibility, and social welfare.

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