1 Introduction

The rail sector is working together to remain competitive and to meet the challenge of making the sector more sustainable, by decarbonising diesel trains, reducing noise and vibration, implementing circular economy initiatives, making passenger trains more attractive or putting goods on board freight trains.

Since the 50s, Talgo has been convinced that weight reduction must be one of the main lines of action to meet the challenges mentioned above. In line with this approach, the new concept of lightweight construction involves replacing conventional materials with new, high-performance materials. An example of this is the frame of the new bogie (Rodal), which is mainly made of composite material (carbon fibre reinforced plastic (CFRP)), with a significant reduction in weight (~50%), resulting in greater energy efficiency and a reduced impact on railway infrastructure, among other benefits.

Today, however, it is unthinkable to manufacture without taking eco-design into account, as circular development models focus on sustainability. These new materials must have recyclability or reusability solutions at the end of their life, avoiding as far as possible energy recovery and end-of-life disposal of materials.

2 Case Study Definition

Firstly, this study is focused on the estimation of the Life Cycle Assessment (LCA) profile of the Rodal by evaluating a set of environmental indicators. Furthermore, an additional objective of, it is a preliminary comparison with the manufacture and use of a conventional Rodal (made in steel) (Fig. 1).

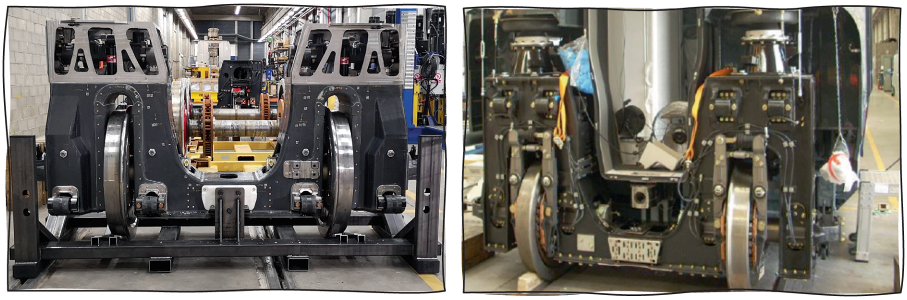

Fig. 1. A running gear: left) frame made of composite; right) frame made of steel.

3 Recycling Process

Potential benefits of the use of lightweight composites in trains could be further enhanced by using recycled materials, such as recycled carbon fibre (rCF) for CFRP.

The thickness and the complexity of the studied piece require the development of a specific process to ensure the final quality of the rCF product. It combines different recycling techniques, obtaining clean recycled fibre, with minimal loss of properties and material, reaching ca. 90% of material recoverability factor. The procedure is as follow:

i. Low **pyrolysis** temperature: gas and liquid fractions generated are internally used as an energy source.
ii. The solid residue is **shredding and sizing** to an optimum size.
iii. Continue with a **solvolysis** to complete removal of the polymer matrix: oxidizing environment and reagents are recovered by distillation.
iv. Fibre is **cleaned** with water (Fig. 2).

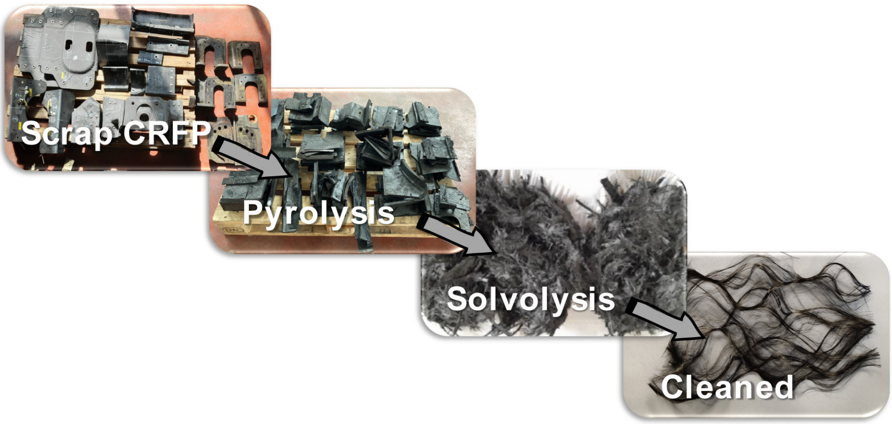

Fig. 2. Process diagram of the carbon fibre recycling process.

4 LCA Study

The increased awareness of the importance of environmental protections, and the possible impacts associated with products, has increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is life cycle assessment (LCA) [1]. For a correct implementation, it is necessary to consider the following stages, according to reference [1]:

- Goal and scope definition.
- Life Cycle Inventory analysis (LCI).
- Impact assessment.
- Interpretation.

The following environmental indicators were selected to characterize the potential life-cycle impacts: global warming, acidification, use of mineral and metal and freshwater and marine eutrophication.

4.1 Goal and Scope Definition

The first goal of this LCA study was defined the environmental life-cycle profile to produce a kilogram of recycled carbon fibre and compare it with virgin carbon fibre. A characterization of the LCA of the lightweight running gear was then analyzed. First, a cradle-to-gate was presented (including production - raw materials extraction and transport to manufacturing sites, manufacturing, and transport stages); secondly the use phase (electricity consumption) is contemplated.

An additional objective was defined to explore the environmental suitability of the lightweight running gear against the conventional one. The comparison is made in two level, including or not the use phase.

LCA – A Kilogram of rCF and vCF

The inventory data for rCF are collected in the following table. The ones necessary for virgin carbon fibre is obtained from the Ecoinvent v3.8 database (Table 1).

Table 1. Main inventory data: inputs and outputs for rCF.

Inputs	rCF		Outputs	rCF	
CFRP waste	1,43	kg	rCF	1,00	kg
Acetic acid	2,46	kg	Aqueous phase	0,0369	kg
Hydrogen peroxide	4,57	kg			
Water	1,07	kg			
Electricity	10,29	kWh			

The advantages of use rCF instead of virgin ones are shown in the following table in terms of the five environmental indicators. The recycling process described above commitments with the circular economy as it allows to increase the recyclability and recoverability of CFRP material, i.e., near 100% on MRF (material recycling factor) which is an improvement from the current state of the art [2] on thermoset material (Table 2).

Table 2. Environmental life-cycle profile: rCF and vCF (virgin carbon fibre).

Impact	vCF	rCF	Units
Global warming	35	12	kg CO_2 eq
Acidification	0,26	0,06	mol H^+ eq
Freshwater eutrophication	0,0068	0,0045	kg P eq
Marine eutrophication	0,032	0,011	kg N eq
Use of minerals and metals	$2{,}8 \cdot 10^{-5}$	1,22·10–4	kg Sb eq

LCA – Cradle to Gate: One Running Gear

The inventory for a piece system was built using data for manufacturing and carbon fibre recycling process. Some data were complemented with the literature data for CFRP production as well as with data from Ecoinvent database for secondary low-alloyed steel, secondary aluminum, and titanium (Table 3).

Table 3. Main inventory data for manufacturing of one Rodal (values per functional unit).

Inputs	Lightweight Running Gear	Conventional Running Gear		Outputs	Running Gear	
Secondary low-alloyed steel	256	743	kg	A piece	1	unit
Secondary aluminium	-	7	kg			
Titanium	26	-	kg			
CFRP	155	-	kg			
Water	731	2122	kg			
Heat	3237	9395	MJ			
Electricity	3181	2625	kWh			

The next table presents the environmental LCA results for one unit of each alternative piece. SimaPro 9.5 software has been used.

Table 4. Environmental life-cycle profile: **cradle-to-gate**.

Impact	Lightweight Running Gear	Conventional Running Gear	Units
Global warming	4,39·103	1,96·103	kg CO_2 eq
Acidification	$2{,}64\cdot10^{1}$	$1{,}02\cdot10^{1}$	mol H^+ eq
Freshwater eutrophication	1,58	$6{,}00\cdot10^{-1}$	kg P eq
Marine eutrophication	4,47	1,76	kg N eq
Use of minerals and metals	2,93·10–2	1,36·10–2	kg Sb eq

With respect to the results, the use of CFRP instead of metal in the lightweight running gear is not justified because the environmental impacts of the conventional running gear are all minor. However, it must be noted that these results do not yet contemplate the use phase.

LCA – Use Phase: One Running Gear

The environmental impacts in terms of the use of a standard train have been obtained from EcoInvent database [3] (Table 5).

It is estimated that a train runs over 500.000 km per year and knowing that its end-of-life (EoL) is about thirty years and a total of 15.000.000 km (Table 6).

Table 5. Environmental impact per kilometer and ton of train.

Impact	Diesel Engine	Electric Engine	Units
Global warming	5,68·10–2	3,87·10–2	kg CO_2 eq
Acidification	6,03·10–4	2,28·10–4	mol H^+ eq
Freshwater eutrophication	6,98·10–6	2,52·10–5	kg P eq
Marine eutrophication	$2{,}58 \cdot 10^{-4}$	$5{,}38 \cdot 10^{-5}$	kg N eq
Use of minerals and metals	2,19·10–7	2,30·10–7	kg Sb eq

Table 6. Environmental life-cycle profile: **use phase**.

	Diesel Engine		Electric Engine		
Impact	Lightweight Running Gear	Conventional Running Gear	Lightweight Running Gear	Conventional Running Gear	
Global warming	3,72·105	6,39·105	2,53·105	4,35·105	kg CO_2 eq
Acidification	3,95·103	6,78·103	1,49·103	2,56·103	mol H^+ eq
Freshwater eutrophication	4,57·101	7,85·101	1,65·102	2,84·102	kg P eq
Marine eutrophication	$1{,}69 \cdot 10^3$	$2{,}90 \cdot 10^3$	$3{,}52 \cdot 10^2$	$6{,}05 \cdot 10^2$	kg N eq
Use of minerals and metals	1,43	2,46	1,51	2,59	kg Sb eq

As makes sense, the greatest environmental impacts come from the use phase.

LCA – Cradle to Cradle

In this analysis is shown the combinate impact of production, manufacturing, transport, and use phase. Thus, the values obtained in Table 4 (cradle-to-gate results) and Table 6 (phase use results) are seen in a full LCA.

The emissions credit represents the effect of the differences in environmental impacts between conventional and lightweight pieces. It is calculated as follows and shown in Table 7:

$$Emissioncredit = Emission_{conventional} - Emission_{lightweight}$$

A positive value would suggest a favorable performance of the piece for the environmental indicator. The environmental benefits associated with the full-life operation of the train with the lightweight piece were found to be much higher than the aforementioned manufacturing penalties.

Table 7. Environmental life-cycle profile: **cradle-to-cradle - CREDITS**

	Diesel Engine	Electric Engine	
Impact	Emission Credit	Emission Credit	Units
Global warming	2,65·105	1,79·105	kg CO_2 eq
Acidification	2,82·103	1,05·103	mol H^+ eq
Freshwater eutrophication	3,18·101	1,18·102	kg P eq
Marine eutrophication	$1{,}21\cdot10^3$	$2{,}50\cdot10^2$	kg N eq
Use of minerals and metals	1,01	1,07	kg Sb eq

5 Conclusion

With the work performed, lightweight structures show benefits from an environmental point to view mainly on CO2 equivalent emission due to use phases.

This work fills the gap in LCA studies on lightweight, waste-based train components by exploring the environmental suitability of alternative pieces for trains based on the use of rCF including a proposal for a new recycling process reaching ca. 90% of material recoverability factor.

Acknowledgement. These studies are included in Rail4EARTH project. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No: 101101917.

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Refining Design Approaches and Implementing the Material Matrix Assessment to Foster Structural Components Circularity

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Abstract. Integrating eco-design strategies is crucial when developing sustainable structural components. In the automotive industry, eco-design strategies are becoming essential as the industry faces pressure to reduce its carbon footprint and comply with regulations to reduce greenhouse gas emissions. Integrating these strategies into vehicles' design and manufacturing processes can significantly improve resource efficiency and reduce emissions, e.g. using lightweight and recyclable materials, such as aluminium, carbon fibre composites, and bio-based plastics, can enhance fuel efficiency and minimise energy consumption. Consequently, refining the eco-design strategies can participate in shifting from traditional linear production into circular design, i.e., using design for repair, reuse, refurbishment, and recycling approaches can limit the generation of waste products and reduce the pressure on the environment by reducing the need to extract raw materials. Several studies explained the best approach to selecting the proper design strategies, and more needs to be done on how the design strategies can be applied to support product circularity. It is crucial to understand that implementing eco-design strategies is challenging, and the main challenge is that product designers and manufacturers need knowledge and awareness. Consequently, incentives to implement eco-design strategies are still immature, and many companies focus on short-term profits rather than long-term sustainability. The archival value of this report is to:

- Define tactics and general circular design approaches (DFX) to preserve structural components and materials integrity.
- Guide designers while considering the product circularity and end of life (EOL).
- Provide an illustrative way to select the best material for the component based on a decision from the material matrix assessment.

Keywords: Design Approaches · Structural component circularity · Material Matrix Assessment · Automotive Industry · Carbon footprint

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 726–732, 2025.
https://doi.org/10.1007/978-3-031-95284-5_101

1 Introduction

Eco-design involves integrating environmental considerations into product design to minimize the environmental impact throughout the product's lifecycle [1]. This includes extracting raw materials, manufacturing, distributing, using, and end-of-life disposal. Designers must consider the product's impact on the environment, such as greenhouse gas emissions, energy consumption, and waste generation, and identify areas where improvements can be made [2, 3]. Many authors have classified and identified strategies, methods, and tools that support product design for facilitating the transition to eco-design. These studies have emphasised the vast and diverse range of supporting approaches and the criteria for selecting the most appropriate eco-design approach [4–6]. Additionally, implementing eco-design strategies can directly improve crashworthiness and vibration performance through proper structure design optimisation. This involves optimising the size, shape, and topology of developed components to reduce material use and enhance structural performance [7].

The automotive sector is under pressure to diminish its carbon footprint to keep up with the EU Fit for 55 and zero carbon by 2050 goals. It has been estimated that up to 80% of all environmental impacts are determined during the design phase of products. That is why the refinement and development of Eco-design strategies and assessments are vital to the industry. Some popular strategies vehicle manufacturers usually rely on are using lighter materials [8], design of assembly/disassembly [3], and designing for remanufacturability [9].

The main challenge in eco-design is the need for product designers and manufacturers to have the right knowledge and awareness. This article aims to help end-users and designers tailor and streamline their approaches by providing guidelines and support in choosing the best circular design for their application.

2 Eco-Design Approaches

The typology of eco-design approaches encompasses diverse strategies and principles aimed at reducing the environmental impact of products and systems. Figure 1 represents the most straightforward framework. These approaches can be broadly categorised into several key themes. One prevalent approach is related to preserving the product's integrity, and the other is keeping the material's integrity.

2.1 Design for Preserving Product Integrity

Product integrity was defined for the first time as the extent to which a product remains identical under the loads encountered during its life cycle [10]. A design approach for longevity, life span extension, and recovery should be applied to maintain product integrity.

The design approach for longevity involves evaluating a product's life cycle to ensure a long lifespan, considering user needs, business objectives, and resource efficiency [10]. Physical durability is crucial, influenced by factors like wear, fatigue, and corrosion, all addressed through strategies such as design for reliability and durability [5, 11, 12]. Designing for life extension in the automotive industry includes choosing robust materials, optimizing maintenance, and adhering to standards like EN 13306:2018 for maintenance types [13]. Maintenance relies on strategies like design for Assembly and Disassembly to facilitate accessibility and reduce costs [3]. Design for recovery aims to salvage economic and ecological value, with options like repair, refurbishing, and recycling considered to maintain product and material integrity [14].

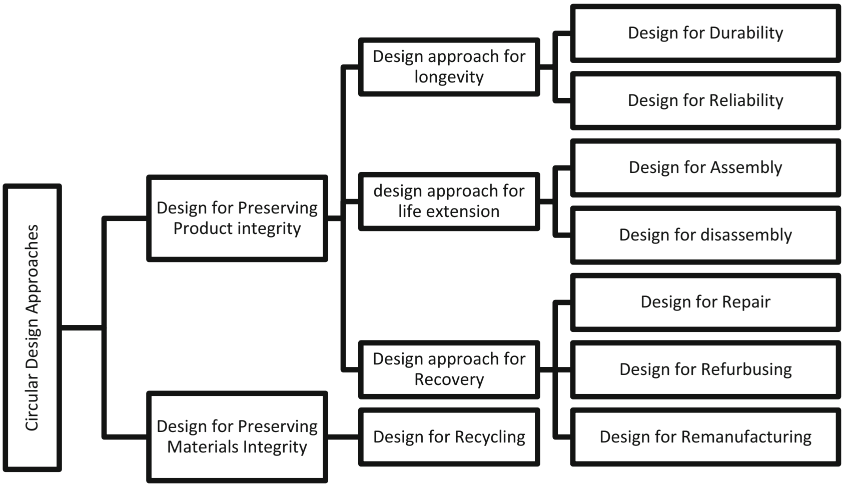

Fig. 1. Typology for design approaches. The chart also shows an example of related DFX strategies that should be implemented.

2.2 Design for Preserving Materials Integrity

Materials integrity significantly contributes to the safety and environmental success of any product/vehicle circularity. Design for recyclability is the leading player in preserving product material integrity and is a crucial eco-design strategy that aims to reduce product environmental impact throughout the product life cycle.

3 Considered Aspects of Eco-Design

Incorporating environmental considerations into product development and redesign is a practice known as eco-design. Eco-design aims to balance ecological and economic requirements by systematically addressing environmental aspects at every stage of the product development process. Its overarching goal is to create products that minimise their environmental impact across the entire product life cycle. Within the framework of eco-design, various design alternatives that align with specific targets and constraints can be evaluated. This evaluation process aligns with eco-design principles emphasising sustainable practices and environmental responsibility. As indicated in Fig. 2, the environmental footprint assessment encompasses various stages of a product's life cycle, including the production phase, use phase, and end-of-life options such as recycling or landfilling. These aspects are integral to the holistic assessment of a product's environmental impact.

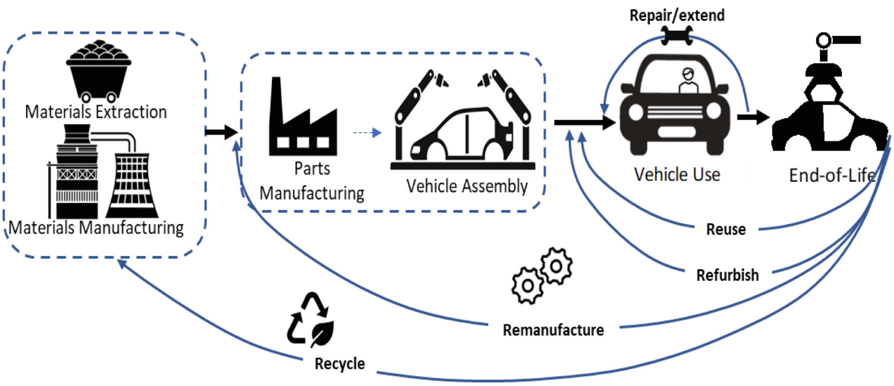

Fig. 2. Product System, showing different vehicle production phases and Eco-design strategies that can be implanted to shift from linear to circular production.

The Production Phase includes critical elements such as raw material extraction, manufacturing of the structural part, and associated logistical activities. The weight of the part plays a pivotal role in raw material extraction and logistics. The efficiency of the manufacturing process, including scrap generation, ratio of faulty parts, and energy and water consumption, is a key focus. Strategies to increase process efficiency include energy-conscious manufacturing, streamlining references, and compatibility with current assembly lines at OEM facilities.

The environmental impact of automotive components is intrinsically linked to their weight due to their direct correlation with the vehicle's energy consumption during its operational phase. While mass-induced fuel consumption (MIF) is comparatively lower in Battery Electric Vehicles (BEVs) than in Internal Combustion Engine (ICE) vehicles, it remains a significant factor [15]. Consequently, weight reduction is the principal approach to diminishing the environmental footprint of a vehicle component throughout its usage period.

The structural constituents of an automobile possess the potential for reuse, refurbishment, recycling, or deposition in a landfill upon reaching the end of its life cycle. Each of these end-of-life routes has its own environmental impact, ranging from minimal to significant. However, except for landfill disposal, the least favourable option, the initial step in the process is dismantling. Designing for disassembly is especially important in cases where a vehicle's components consist of multiple materials, as specific joining methods can complicate the sorting process and may even hinder recycling efforts [3].

4 Implementing Material Matrix Metrics

When considering eco-design, designers can make informed choices based on carefully curated parameters that balance ease of assessment with environmental impact relevance. These parameters can be defined based on the project's target. Table 1 depicts examples of the metrics parameter and the weighting factor.

Table 1. An example of the Material Matrix Metrics parameters and the weighting factor.

Metrics parameter	Meaning and method of evaluation
Potential for Weight Reduction	Achieving weight savings is critical for reducing environmental impacts and costs. It is directly linked to energy consumption during production and usage. A simplified assessment using alternative material density is needed, followed by a more precise evaluation tailored to the chosen material and manufacturing
Process Recyclability	This factor considers the recyclability of the material. It is evaluated on a scale of 1 to 3: 1." Not recyclable with conventional techniques" 2." Difficult to recycle with conventional technics." 3. "Easily recyclable"
Assembly/disassembly	the complexity of the assembly/disassembly is related to the lifecycle: production (simple assembly methods increase the manufacturing efficiency), use (to allow maintenance) and end-of-life (to allow easy sorting for reuse, refurbishment, and recycling) 1. "Currently not disassembled, medium complexity for assembly (welding)", 2. "Difficult to assemble/disassemble" (adhesives) 3. "Easily as assemble/disassemble" (bolts)
Reduction of references	integrating different functions in fewer parts contributes to cost-effectiveness and environmental footprint reduction. This metric is measured in terms of the total number of parts saved. The decrease in references can be implanted only by understanding the part's complexity and the manufacturability
Compatibility with the current assembly line	This metric is evaluated on a scale of 1 to 3: 1. "Significant changes on the assembly line are required" 2." Minor changes on the assembly line are required." 3. "No changes required"

Let's consider a hypothetical scenario to understand the material matrix's importance in achieving product circularity. Designers need to establish specific criteria for any redesign, such as weight reduction, use of available materials, manufacturability, performance standards, and maintenance facilitation. By following the following steps, a decision can be made efficiently regarding the suitability of different materials for specific subcomponents:

- **Comprehensive Evaluation:** Each design will undergo a thorough assessment based on the established criteria. For example, manufacturability will be assessed in collaboration with part manufacturers and process experts, and crash performance will be simulated to ensure compliance with safety standards.
- **Environmental Assessment:** Designs that successfully meet the predefined criteria will then be subject to an environmental evaluation using specified metrics.

- **Scoring and Weighting:** Ultimately, a score will be assigned to each design in accordance with each category, and these scores will be weighted accordingly.

Then, to calculate the global score of each alternative design, different scores of each parameter will be weighted as per project or condition.

5 Conclusions

In conclusion, this paper investigated the possibilities of redesigning products to align with eco-environmental goals. While the eco-design approaches explored in this study share many commonalities with existing strategies concerning product and material integrity, we introduced a novel and practical tool, the Material Matrix Assessment. The Material Matrix can be used to enhance decision-making when selecting the optimal material for structural components. Our paper not only outlined the concept but also provided a step-by-step procedure for implementing the Material Matrix Metrics, accompanied by an example. By doing so, we aimed to contribute to the growing body of knowledge in eco-design and empower designers and engineers to make more informed choices that can positively impact both the environment and product sustainability.

Acknowledgment. All authors acknowledge EC for funding this work. The research leading to this work is part of the EU-funded Horizon Europe SALIENT project (EU GA No. 101069600 and UKRI GAs No. 10047227 and No.10047305).

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Feasibility of Concrete Paving Blocks Produced with By-Products from Construction and Coconut Industries

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Abstract. This paper aims to analyze concrete paving blocks (CPB) with construction and demolition waste (CDW) and coconut fibers (CF) for light traffic road pavements, applying physical and mechanical characterization. Therefore, nine mixtures, three without by-products, three with CDW recycled materials, and three with CF, were used to produce rectangular CPB 20 cm × 10 cm × 8 cm (length × width × thickness). Tests, such as water absorption, air void, and compressive strength at 7 and 28 days, were done on CPB. The results showed that the mix with CDW materials, 75CDW-0.73, presented CPB at 28 days with the lowest average air void of 11.88%, demonstrating the significant compactness by the jackhammer in mixing recycled aggregates with the water/cement ratio of 0.73. Furthermore, the mixtures REF-0.63F and REF-0.73 presented CPB at 28 days with a characteristic compressive strength 139.33% and 148.42% higher than the mix REF-0.63, being a positive effect of CF and water for the mixtures' workability. Also, the mixtures REF-0.73 and 75CDW-0.73 showed average water absorption below the Brazilian and European specifications of 6%. Finally, the CPB application with by-products is possible for light traffic according to the Australian specification for bike paths or parking areas.

Keywords: Concrete Paving Blocks · Construction and Demolition Waste · Coconut Fibers · Physical and Mechanical Characterization

1 Introduction

The interlocking pavement (IP) consists of a flexible, rigid, or semi-rigid structure, depending on the composition of the base and sub-base layers. These two layers can be roller-compacted concrete for rigid pavement, graded crushed stone treated with cement

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 733–739, 2025.
https://doi.org/10.1007/978-3-031-95284-5_102

or soil-cement for semi-rigid pavement, and simple crushed stone for flexible pavement. Furthermore, the IP layers above the foundation are the sub-base, the base, and the surface (concrete paving blocks, bedding sand, and joint material).

The IP adaptable structure assessments must be made during the planning of this structure. For a more effective construction, the concrete paving blocks (CPB) must show mainly mechanical and physical properties, such as compressive strength and water absorption, according to standards: Brazilian ABNT NBR 9781 [1], European CEN EN 1338 [2], and Australian SA AS/NZS 4456.4 [3].

By-product reuse is an alternative strategy to manufacture CPB. Due to civil construction activities, construction and demolition waste (CDW) is widely generated in urban centers. In Fortaleza, Brazil, the amount of CDW destined for the 61 eco-points is 276,000 tonnes per year [4]. Also, CDW activities generated over 850 million tonnes of by-products in the EU [5]. Another by-product is coconut fiber (CF) from the coir's waste. During their decomposition, 80% to 85% of the coconut weight becomes waste, and their disposal causes a decrease in the lifetime use of landfills [6]. Then, in Brazil and Portugal, Francisco et al. [7] and Cravidão [8] evaluated the application of CDW recycled aggregate and fiber, respectively, for concrete.

Finally, this paper aims to analyze the feasibility of CPB with recycled aggregates from mixed CDW and CF for light traffic road pavements, applying physical and mechanical characterization.

2 Experimental Program

2.1 Materials

Natural materials were gabbro-diorite, 12/20 mm and 6/12 mm gravels (coarse aggregates), and crushed sand 0/4 mm (fine aggregate). Two mixed CDW's recycled coarse aggregates (12/20 mm and 6/12 mm gravels) and a recycled fine aggregate (sand 0/4 mm) were used. CF had an average length of 130 mm. High-early-strength Portland Cement, CEM I 42,5 R, and water were also used. Figure 1 and Table 1 show the aggregates' granulometric composition and materials' physical characteristics.

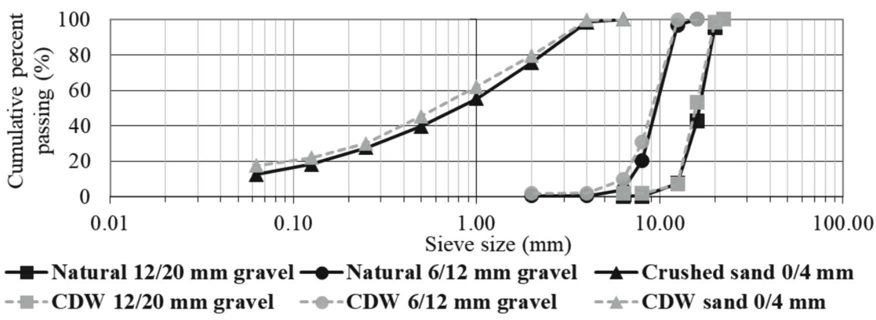

Fig. 1. Aggregates' granulometric composition.

Table 1. Materials' physical characteristics.

Materials	Dry density [9] Mg/m^3	Bulk density [10] Mg/m^3	Water absorption [9] (%)	Fines under 0.063 mm [11] (%)
Natural 12/20 mm gravel	2.85	1.45	0.42	0.20
Natural 6/12 mm gravel	2.84	1.44	0.51	0.24
Crushed sand 0/4 mm	2.72	1.67	0.93	11.98
CDW 12/20 mm gravel	2.22	1.13	5.78	0.76
CDW 6/12 mm gravel	2.26	1.14	6.01	0.99
CDW sand 0/4 mm	2.16	1.42	5.81	17.20
Cement	2.97	–	–	–
CF	–	1.42	140.0	–

Note: the mixed CDW's composition by mass is 42.5% concrete particles, 32.1% rock fragments, 22.8% red bricks, and 2.6% wood, plastic, and bitumen

2.2 Concrete Mixes and Tests on Concrete Paving Blocks

Nine mixtures for dry concrete were used with three water/cement ratios of 0.63, 0.73, and 0.83, a CDW replacement level of 75% by aggregate weight, and a CF addition of 0.1% by mix weight. Therefore, there are three mixes without by-products (REF-0.63, REF-0.73, and REF-0.83), three with CDW recycled materials (75CDW-0.63, 75CDW-0.73, and 75-CDW-0.83), and three with CF (REF-0.63F, REF-0.73F, and REF-0.83F). It is essential to highlight that, to keep the materials' proportions in the reference mixes, the mortar (70.05%) and moisture (7.80%) contents of the concrete were kept constant. The nine mixtures tested are shown in Table 2.

Rectangular CPB 20 cm × 10 cm × 8 cm (length × width × thickness) were manufactured in wooden molds using a jackhammer (model 638 from Kango brand), with a 750 W engine responsible for vibration. The following tests were made on the hardened CPB at 7 and 28 days: air void (three blocks) [12], water absorption (three blocks), and compressive strength (six blocks) [1].

3 Results and Discussion

The average air void, water absorption, and characteristic compressive strength for CPB are shown in Figs. 2, 3, and 4, respectively, with standard deviation bars.

In Figs. 2 and 3, the alternative mix 75CDW-0.73 presented the lowest average air void of 11.88%, related to the second-lowest average water absorption of 5.58%. The compactness of the jackhammer may explain this finding because, according to Chu et al. [13], with an appropriate packing density optimization, CPB with only recycled aggregate showed a 156% compressive strength increase from 30.9 MPa to 79.2 MPa. Then, the material packing by the jackhammer in mixing recycled aggregates with the water/cement ratio of 0.73 provided a significant compactness of the concrete.

Table 2. Concrete components' consumption.

Mixtures	Consumption (kg/m^3)							
	Cement	Natural aggregates			CDW recycled aggregates			Water
		Crushed sand 0/4 mm	6/12 mm gravel	12/20 mm gravel	Sand 0/4 mm	6/12 mm gravel	12/20 mm gravel	
REF-0.63	269.7	1257.0	531.4	121.4	–	–	–	169.9
REF-0.73	228.3	1269.3	520.5	118.7	–	–	–	166.7
REF-0.83	202.7	1307.7	527.1	119.6	–	–	–	168.3
75CDW-0.63	244.8	285.2	120.6	27.5	855.7	361.7	82.6	154.2
75CDW-0.73	212.0	294.7	120.8	27.6	884.0	362.5	82.7	154.8
75CDW-0.83	182.3	293.9	118.5	26.9	881.7	355.4	80.7	151.3
REF-0.63F	261.9	1220.4	515.9	117.8	–	–	–	165.0
REF-0.73F	230.1	1279.2	524.5	119.6	–	–	–	167.9
REF-0.83F	195.8	1262.7	509.0	115.5	–	–	–	162.5

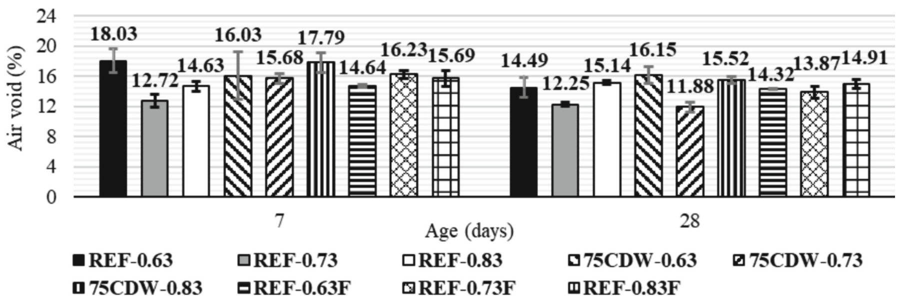

Fig. 2. Concrete mixtures' average air void.

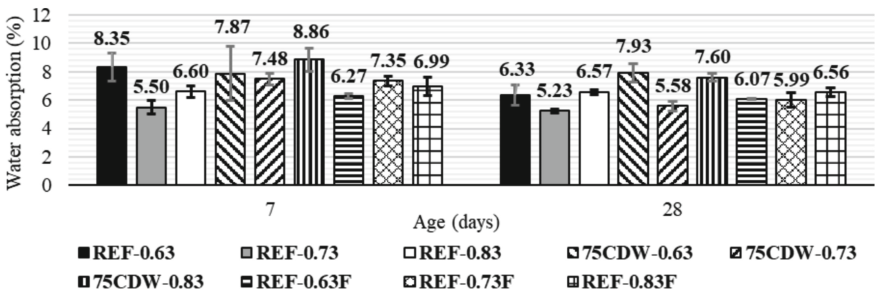

Fig. 3. Concrete mixtures' average water absorption.

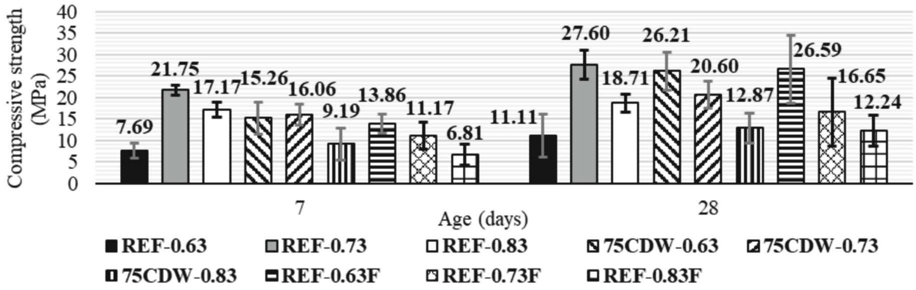

Fig. 4. Concrete mixtures' characteristic compressive strength.

In Fig. 4, the mix with CF, REF-0.63F, presented CPB at 28 days with a characteristic compressive strength 139.33% higher than the reference mixture with the same water/cement ratio, REF-0.63 (26.59 MPa > 11.11 MPa). This positive effect of adding CF may be due to the fiber's potential to minimize concrete cracking when applying vertical loads [14]. Furthermore, the reference mixture with more water, REF-0.73, showed a characteristic compressive strength 148.42% higher than the reference mix with less water, REF-0.63, at 28 days (27.60 MPa > 11.11 MPa). As dry concrete has reduced water content, the laws that explain the mechanical properties of dry concrete are not always similar to mixes of consistency plastic [15]. Then, adding more water can improve the mixtures' workability, favoring the compressive strength increase.

Positively, in Fig. 3, the mixes REF-0.73 and 75CDW-0.73 showed average water absorption at 28 days (5.23% and 5.58%) below 6.0%, a specification of the standards ABNT NBR 9781 [1] and CEN EN 1338 [2]. Negatively, in Fig. 4, all the mixtures presented compressive strength results below 35 MPa, a Brazilian specification for special and commercial vehicles at 28 days [1]. However, the Australian standard SA AS/NZS 4456.4 [3] states a minimum compressive strength of 15 MPa for CPB in cycle paths and parking areas. Finally, new criteria for bike paths with a lower specification can be created for the Brazilian standard ABNT NBR 9781 [1].

4 Conclusions

This paper presented research with the primary objective of analyzing the feasibility of CPB with recycled aggregates from mixed CDW and CF for light traffic road pavements. With the main results, the leading direct inferences can be as follows:

- The material packing by the jackhammer in the alternative mixture, 75CDW-0.73, with a water/cement ratio of 0.73, was a key factor for the greater compactness of this mix, showing the lowest average air void of 11.88%.
- The mixes REF-0.63F and REF-0.73 presented a characteristic compressive strength 139.33% and 148.42% higher than the reference mixture REF-0.63 at 28 days. Then, adding CF and water with compacted energy can significantly improve the workability and mechanical behavior of the concrete.
- All the mixes showed characteristic compressive strength results below 35 MPa, a Brazilian specification. However, according to an Australian specification of 15 MPa for CPB, a new category for bike paths or parking lots can be made.

Finally, this study recommends using CPB in areas with little to no motorized traffic. It also supports CPB on low to intermediate-trafficked roads but notes the need for adaptation.

Acknowledgments. The authors acknowledge the CERIS's labs in the Instituto Superior Técnico and the companies Tecnovia, Cimpor, RCD S.A., and Iapacoco Nordeste for making materials available for this research. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior–Brasil (CAPES) – Finance Code 001.

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How Does Circular Economy Disrupt Business Models: The Case of Ballast Reuse in Railway Projects

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Abstract. The European rail infrastructure industries are incited to rethink their supply chain to achieve carbon neutrality by 2050 (European Green Deal). This leads them to undertake a paradigm shift from a linear to a circular economy based on reusing and recycling materials.

However, industries may be reluctant to invest in new circular models when they lack in estimating the potential benefits and costs of the new circular businesses. Nevertheless, the Ellen MacArthur Foundation argues that a circular economy develops new and strategic opportunities and generates benefits if well thought out.

This paper analyses the economic impact of moving from a linear to a circular economy, focusing on the ballast reuse for rail regeneration projects for the case of SNCF Réseau. We propose a multistakeholder activity-based costing approach and apply it to three ballast supply scenarios.

The results show that reusing ballast generates winners and losers. While it can be economically attractive for a project to reuse its ballast, it becomes more complex to determine the profitability of reusing ballast for sharing between different project sites; additional parameters should be considered, such as the distance between sites or to ballast pits as well as other environmental costs. The paper thus argues that circularity does not always equate to sustainability. The deployment of a circular economy should require a systemic vision that not only allows one to pilot a project but also to map and interact with its industrial environment.

Keywords: Circular economy · Railways · Ballast reuse · Activity-based costing · circular supply chain

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 740–746, 2025.
https://doi.org/10.1007/978-3-031-95284-5_103

1 Introduction

The ecological transition is prompting rail infrastructure managers to rethink and innovate their supply markets. For example, the French railway infrastructure manager, SNCF Réseau, has targeted collecting 100% of the structural materials used in railroad construction (rails, sleepers, ballast, and copper) for recycling. The company thus undertakes a shift from a linear economy based on the end-of-life concept to a circular model based on reusing and recycling materials.

Despite SNCF Réseau's stated ambitions, the literature tells us that such a transformation can be challenging due to barriers, such as the need for more communication between stakeholders [1], or the capacity to invest in new circular models [2]. However, the main obstacle concerns the lack of estimation of economic benefits [3].

Economic benefits are either the main driver or the primary barrier to adopting circular models [4]. Companies are reluctant to invest in new circular models that may be costly in the short term or economically unprofitable in the long term. However, if well designed, a circular economy may develop strategic opportunities while generating benefits.

Several tools and methods exist for estimating and subsequently improving the economic (and extra-financial) impact of integrating circular activities into companies. These methods are based on weak sustainability, where sustainable development capitals are substitutable [5]. These methods can make more explicit the trade-offs involved in achieving the best overall corporate performance, i.e., the best strategy and organization of resources. However, this point of view is not always shared in the literature, as it can be considered anthropocentric when the interest driving the company's change is economic rather than environmental [6]. In this article, we hypothesize that linking circularity to economics can facilitate corporate decision-making and change management. The monetarization methods provide an evaluation criterion for product and project design, allowing industrials to compare their different strategies regarding a standard reference and guiding their choices toward the optimal solution from an economic, social, and environmental point of view. However, we do not mean economic profitability should be the only motivator for moving to circular businesses.

Traditional economic evaluation methods include cost-benefit analysis [7], generally used on projects to measure the socio-environmental impact of a project; the activity-based costing approach [8], used to estimate the cost of a product through the activities carried out to design it; or lifecycle costing [9], revealing the cost of a product throughout its lifetime.

This paper adds to the literature an example of the impact of adopting circular business models in companies. Our research is based on the action research paradigm [10] used in the literature to solve a problem of real situations with continuous transformation thinking. More specifically, we focus on the monetary impact of ballast reuse in railway projects. To this end, in Sect. 2, we adapt the activity-based costing approach to multiple stakeholders. The results of this approach's application are presented in Sect. 3 and discussed in Sect. 4.

2 Methodology

The research was conducted during two months at the end of 2022 in SNCF Réseau under the lead of two in-house experts in charge of deploying ballast reuse in railway projects and with the help of other experts and based on the internal investigation and document analysis. The work aimed to study the direct costs and profitability of reusing railway components, in this case the ballast, and how the reuse process can lead to the introduction of new ways of proceeding within the company.

That is why, this paper compare the profitability of three ballast supply models that can be used in a railway regeneration project: (1) the conventional linear model where old ballast is removed and replaced by a new ballast from external quarries; (2) a circular model where the ballast of a project site is reused onsite; (3) a second circular model where a project site transfers its old ballast to another project site to be reused. We focus in our analysis on the economic impact on the internal stakeholders in the company regarding these three models.

Since the purpose of our work is to understand the potential improvements enhancing ballast reuse at a significant level in the company, we decided to use a multistakeholder activity-based costing (we will call MS-ABC) adapted for industrial projects.

The traditional activity-based costing (ABC) approach is used in the literature for assigning direct and indirect costs to an industrial product, considering the activities carried out to manufacture this product [11]. ABC contrasts with conventional costing systems as it considers that a product consumes activities that consume resources. Over the years, it has acquired the ability to drive change in product design and manufacturing processes as it can be used as a decision-support information system [12], identifying potential cost drivers. ABC is composed of two stages. The first one consists of identifying the main activities and assigning their costs. The second stage allocates each activity's cost to the product.

ABC has inspired other methodologies such as Feature costing [13] based on the variation of costs according to the different possible features of products. More recently, [12] have proposed an ABC based on matrix multiplication that transforms the two ABC steps into two matrices, which combination represents a product-resources matrix. Finally, time-driven ABC has also been used, arguing that costs and revenues depend on resources and time [14].

In this research, we choose to use ABC since it considers that a product is a succession of activities, which also defines a project. However, as rail projects may involve several internal stakeholders, we needed to adapt ABC to attribute each activity's cost and benefit in a ballast reuse project to the stakeholder concerned.

Figure 1 presents the four steps of our MS-ABC. For each ballast model, the methodology consists of (a) mapping the potential internal stakeholders; (b) unfolding the activities executed in the model; (c) assigning activities to the stakeholders; and (d) attributing the cost or benefit of each activity according to each actor, knowing that the cost of an activity may depend on many variables. For example, the cost of transporting ballast to project site depends on the transportation mode. In this paper, we only focus on direct costs, i.e., we do not consider monetary values such as the cost of carbon emissions. In the end, a comparison of the three ballast supply models allows us to assess the profitability of each of the model regarding a particular stakeholder.

Our methodology differs from cost-benefit analysis in that it calculates profitability per activity to a given stakeholder. It also differs from lifecycle costing in considering an activity as a transaction between stakeholders.

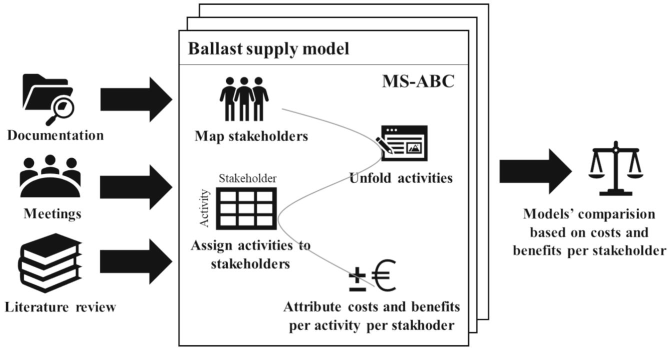

Fig. 1. Overall methodology

3 Results

The methodology is applied to the three ballast models described in the previous section. The final results are shown in Fig. 2. Only standardized costs have been displayed for confidentiality reasons, while the ratio between them remains valid. We mainly observe that:

- For the standard ballast supply model (BM1), two main entities within the company are involved: an internal supplier responsible for purchasing and trans-shipping ballast, and the project to which the ballast is finally invoiced. While the supplier's profit depends on the transported ballast, the project costs mainly depend on the ballast acquisition and the landfilling (stock and watering). The project can, however, generate a benefit if it can sell its old ballast.
- We found no internal supplier for the second model (BM2), which consists of reusing ballast onsite (assuming 100% of the ballast is reused). The project considerably reduces its expenditure, which now depends on ballast screening and washing. Finally, there is no cost of landfilling (stock and watering) since the project no more needs to stock new ballast.
- In the third model (BM3), a supplier project (or ceding project) transfers its ballast to a buyer project for free; the supplier project gains nothing (voluntary model). The buyer project costs depend on transport, screening and washing, and landfilling (stock and watering); the ballast acquisition costs are thus saved. In general, the distance between the two project sites is short in order to reduce ballast transport costs. In addition, in this model, the two projects must Note that, in this model, the internal supplier plays no role, which represents a loss for him and a potential impact on other projects using the standard model.

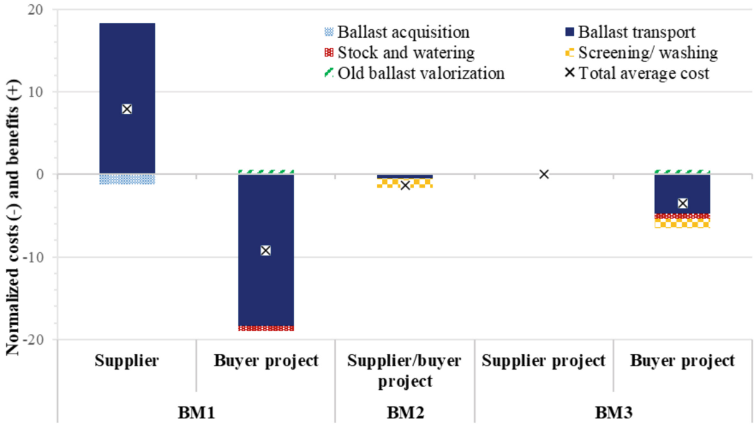

Fig. 2. Costs per ballast model, activity, and stakeholder

4 Discussion and Conclusion

The results show that adopting circular models upsets current balances as it can generate a win-lose situation. For example, in our case, the internal supplier is affected when two projects collaborate (BM3); this can potentially negatively impact projects using BM1. Innovating in the processes and rethinking roles is thus essential.

We also find that on-site ballast reuse (BM2), if the ballast quality permits, is the most economically profitable model for a project. Therefore, when a project manager is well-informed and accompanied by environmental experts, he will have no reason not to reuse the project's ballast. This solution could easily be deployed on a large scale in the industry.

BM3 shows that voluntariness is the main factor for exchanging ballast between projects since there are no economic transactions between the two projects. Here, we argue that the industrialization of circular models can be hindered since that the supplier project has no economic incitation for transferring its ballast. We can thus imagine creating a marketplace for buying and selling ballast. This needs to fix a new way of calculating the ballast economic value as well as to promote new processes in the company. Indeed, we note that ballast transport is highlighted as the most impactful activity in all models. It represents the most expensive activity. It depends on many features, such as the transport mode or the distance between quarries or project sites. During our data collection, we analysed the ballast transport scenarios. We noticed that the standard model BM1 may be more profitable for a project than the circular BM3 if the project is near a quarry. In addition, when calculating the carbon emissions of ballast supply, we find that transport is the leading emitter activity. In other terms, depending on the features, circularity does not always imply sustainability since BM1 may sometimes be less polluter than BM3. This leads to performing our actual methodology exclusively based on direct costs. To assess the overall profitability of circular models, we need to integrate other indirect costs linked to carbon emissions or ballast scarcity. Although the literature on environmental monetarization is rich, we noticed that project managers only sometimes understand the proposed economic values. That is why we restricted this study to direct costs in a project budget. We emphasize the need for more disclosure on these issues. Nevertheless, our methodology is interesting in allowing us to represent the gains and losses per stakeholder. It allows managers and experts to understand the possible conflicts that could emerge when designing business models.

To conclude, deploying circular models must be economically profitable, but the economic criterion needs to be revised. As we have shown, circularity is not synonymous with sustainability. Companies, therefore, need to innovate and train project managers to enable them to deal with a new, shifting, and complex project environment.

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Life Cycle Analysis of Low Carbon Roller Compacted Concrete Pavements

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Abstract. Roller compacted concrete (RCC) is a zero-slump concrete with lower ordinary Portland cement (OPC) content and water/cement, and a higher proportion of aggregates than conventional concrete. Life cycle analysis (LCA) was performed with a cradle-to-gate system boundary to compare the impacts of continuously reinforced concrete pavements (CRCP) and RCC pavements per mile of dual carriageway. RCC pavements have less than half of the environmental impact of CRCP due to lower thickness of RCC pavement lifts and lower quantity of OPC. Construction processes contributed to only a very small proportion of the total environmental load for both pavement types. In RCC pavements, notable reductions in the GWP were observed with partial replacement of cement. Compared to fly ash and ground granulated blast furnace slag, limestone calcined clay cement has the lowest CO_2e emissions for concretes with similar compressive strength, due to its shorter transport distances. The benefits of using recycled concrete aggregates and reclaimed asphalt pavement aggregates in RCC pavements were outweighed by their long transport distances. The geographic availability of materials is critical to consider when replacing OPC and natural aggregates to reduce RCC pavement environmental impacts.

Keywords: Roller compacted concrete · life cycle analysis · cement replacement · non-virgin aggregates · global warming potential · abiotic depletion

1 Introduction

The global popularity of concrete pavements for use in high-speed applications is growing because of their longer design life over asphalt pavements due to their higher durability, stiffness, and improved performance in a range of temperatures [1–3]. Furthermore, it's important to note that concrete pavements offer a significant advantage in terms of routine maintenance costs. They have been consistently proven to be the least costly option over the long term, requiring fewer repairs and resurfacing compared to asphalt alternatives. This cost-effectiveness makes concrete pavements a highly attractive choice

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 747–753, 2025.
https://doi.org/10.1007/978-3-031-95284-5_104

for sustainable and economically viable infrastructure projects worldwide [4]. However, cement contributes up to 90% of greenhouse gas emissions associated with concrete production, with clinker attributable to 60% of UK CO_2 emissions from concrete and cement production [5]. Roller compacted concrete (RCC) pavements provide opportunities for reducing these environmental impacts due to their lower cement content. They combine the durability of conventional concrete pavements with the ease of construction of asphalt pavements using high-compaction pavers and vibratory rollers [1]. The environmental benefits could be further exploited through partial substitution of OPC with fly ash, ground granulated blast furnace slag (GGBS), and limestone calcined clay cement (LC3) and of natural aggregates with recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) aggregates.

Life cycle assessment (LCA) quantitatively evaluates the sustainability of producing RCC pavement over its entire life. Both one cubic metre (m^3) and one kilometre (km) of RCC pavement have been used as functional units for existing LCAs, with system boundaries ranging from cradle-to-gate to cradle-to-grave [6–9]. Studies by Hashemi et al. (2020) and Anastasiou et al. (2015) found that partially replacing OPC with fly ash (45% and 50% respectively) reduced global warming potential per m3 by 40% and per km by 60% [7, 8]. Adamu et al. (2018) and Hashemi et al. (2020) also showed OPC replacement rates of 38–45% using fly ash or GGBS decreased CO_2 emissions by 39–40% [7, 9]. However, long transport distances for fly ash and GGBS, discussed by Kurda et al. (2018) and Adamu et al. (2018), should not be overlooked [9, 10].

LCA of RCC with the replacement of natural aggregates with RAP aggregates has been investigated by Debbarma et al. (2021) and Shi et al. (2018) with contrasting findings [11, 12]. A 50% replacement rate was shown to reduce the CO_2e emissions by 1.5% for the former and a 40% replacement rate was shown to increase the GHG by 3% for the latter. Other non-virgin aggregate replacements have been investigated by Aghayan et al. (2020), Anastasiou et al. (2015), and Adamu et al. (2018), with similar patterns of small increases or decreases in the GWP [8, 9, 13]. The impacts of mixes with non-virgin aggregates are more greatly influenced by their longer transport distances and are sensitive to differences in the assumed distances across the LCA.

This paper aims to quantify the environmental impacts of RCC pavements and the effect of low carbon substitutions on GWP and abiotic depletion (ADP) of fossil fuels.

2 Experimental Program

OpenLCA, an open access, robust tool for conducting LCA was used to determine the environmental impacts of RCC pavements. CML 2001 1A Baseline mid-point impact assessment method was used for impact assessment. The main environmental impacts were the GWP over 100 years and the abiotic depletion (ADP) of fossil fuels.

2.1 Life Cycle Analysis ISO 14040

The functional unit considered was one mile of dual carriageway with a minimum target compressive strength of 40 MPa at 28 days for the concrete mixes analysed [14, 15]. The system boundaries were cradle-to-gate with a construction phase accounting for the fuel, energy, and water inputs of the processes. The inventory consisted of supply-chain data from the Ecoinvent 3.7 Database and information obtained from the literature and Environmental Product Declarations (EPDs). The provider regions were chosen to be the UK, then Europe or a European country, with the Rest of the World average as a last resort. Table 1 shows the mix pairs of similar strength obtained from the literature, allowing for more valid comparisons of percentage change of impacts. The pavement width of 21.1 m was designed per DMRB CD 127 guidelines [16]. Following DMRB CD 226 and 224, the lift thicknesses were designed to be 270 mm and 200 mm for CRCP and RCC pavements respectively [14, 17]. For transport, single trip distances were obtained from various literature and are detailed in Table 2. Machine specifications were used to obtain the required information about the construction processes to enable the impacts of these processes to be calculated.

Table 1. Concrete design mixes used in LCA analysis.

Substitution	Literature	Mix
Reference RCC	Mohammed (2018) [18]	Granite mix
Reference OPC	Zimmerman & Lehký (2014) [19]	C40/50
RCC with fly ash	Tangtermsirikul et al. (2004) [20]	RCCP:31 & RCCP: 17
RCC with GGBS	Afroughsabet (2021) [21]	RCC REF & LCC RCC
RCC with LC^3	Dhandapani et al. (2018) [22]	Mohammed (2018) in proportions [17]
RCC with RAP aggregate	Mahdavi et al. (2021) [23]	R0 & R25
RCC with RCA	Nehar et al. (2022) [24]	100% NA & 25% RA

Table 2. Transport distances of materials.

Material	Distance (km)
Portland cement	105
Fly ash	155
GGBS	220
LC^3	110
Natural aggregates	55
Non-virgin aggregates	140
Reinforcing steel	250
Concrete	12

3 Results and Discussion

3.1 RCC Pavements vs CRCP

Figure 1(a) and (b) show that RCC pavements have a lower environmental impact per mile across all processes within the system boundaries. The concrete mix accounts for 85% of the GWP for RCC pavements and 93% of CRCP. The difference is attributable to the smaller required thickness and lower cement content of RCC pavement lifts for the same design parameters as CRCP. The impacts of construction account for 0.05% and 0.1% of the GWP and ADP respectively for RCC pavements. Transport of constituents accounts for a higher percentage of the overall environmental impacts for the ADP than for the GWP, of which 85% of the constituent transport impacts are due to aggregate. The findings align with Hashemi et al. (2020) and Adamu et al. (2018) when considering the same boundaries and functional units [7, 9].

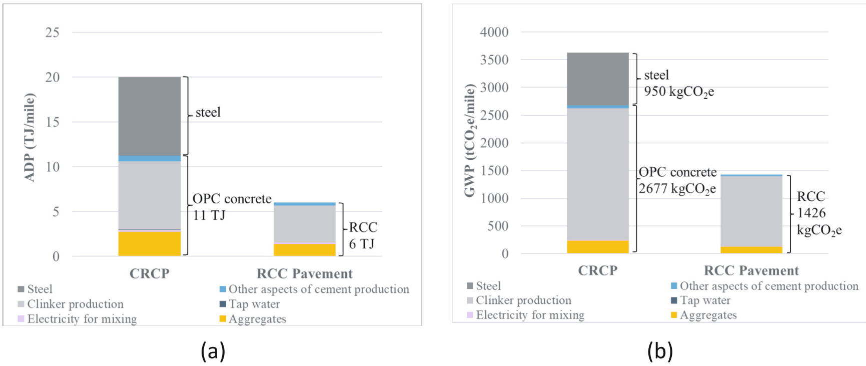

Fig. 1. Comparison of ADP and GWP of CRCP and RCC pavements

3.2 Ordinary Portland Cement Replacement

Substitution of OPC saw a 30–40% reduction in the GWP and a 6–24% reduction in the ADP depending on the material. LC3 with 50% replacement of OPC saw the greatest savings in the GWP per kilogram of OPC substituted when compared to the fly ash and GGBS mixes. However, as this mix was only hypothetical, it requires testing before it can be proposed for high-speed pavement applications. For the ADP, 50% fly ash substitution of OPC saw the overall greatest reductions per kilogram of OPC replaced, compared to GGBS and LC3. For both GWP and ADP, the mixes using fly ash and GGBS resulted in an increase in the environmental impacts due to constituent transport distance being 1.5 and 2 times longer than that of OPC respectively, which is in alignment with literature [7, 8].

3.3 Natural Aggregate Replacement

Natural aggregate replacement with RAP/RCA aggregates saw a small increase in the GWP (0.1%) and ADP (1%). Whilst there is a reduction in the environmental impacts associated with the concrete mixes in both substitutions, these are outweighed by the increase in the impacts associated with constituent transport for the system boundaries and assumptions made in this analysis. The longer transport distances of these non-virgin aggregates assumed 2.5 times that of virgin aggregates, cause this overall marginal increase in the impacts due to RCC pavements.

3.4 Sensitivity Analysis

The LCA showed that the environmental impacts of RCC pavements are most sensitive to the pavement lift thickness as they are directly proportional (See Fig. 2(a)). RCC pavements are also greatly influenced by the percentage of OPC replacement, with an overall decrease in the GWP of 12.7 tCO_2e/mile per percentage replacement of OPC (See Fig. 2(b)). This is compared to natural aggregate replacement where there is an overall increase in the GWP of 0.78 tCO_2e/mile per percentage substitution. Hence, it can be concluded that impacts are insensitive to changes in natural aggregate replacement rate for RCC pavements.

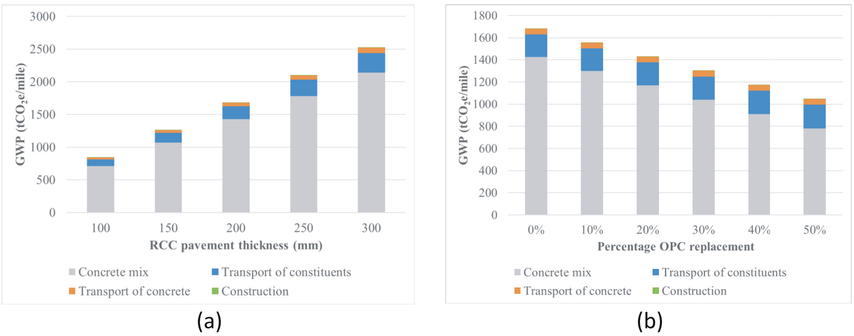

Fig. 2. Effect of pavement thickness and OPC replacement on GWP

Finally, the sensitivity to transport distances was analysed. Overall, there was very little change in the total environmental impacts when the assumed transport distances for OPC, aggregates, and concrete were separately adjusted. The GWP and ADP were affected most by changes in the aggregate transport distance, however, this was still relatively insignificant compared to the variations in the total environmental load due to changes in the lift thickness and OPC replacement rate.

4 Conclusions

Based on the LCA the following conclusions about RCC pavements are made:

(1) RCC has a GWP and ADP less than half that of conventional concrete pavements, providing a viable solution to reduce the environmental impacts.
(2) Replacement of OPC with SCMs can reduce the GWP of RCC pavements by 30–40% per mile of dual carriageway, with LC3 providing the greatest savings.

(3) Natural aggregate replacement with RCA and RAP aggregates increases the environmental load of RCC pavements by 0.1–2.5% per mile of dual carriageway demonstrating the impact of long transport distances of nonvirgin constituent.
(4) RCC pavement impacts are directly proportional to the pavement lift thickness and are also heavily impacted by changes in the OPC replacement rate.

In general, the geographic availability of materials is an important consideration to reduce the environmental impacts of RCC pavements in addition to low clinker content.

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The Norwegian Approach to Future Design, Construction, Maintenance, and Rehabilitation of Asphalt Pavements

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Abstract. Many actions are being undertaken by Norwegian road owners to reduce the environmental impact of construction and maintenance of pavements. Thanks to the collaboration with the local contractors association, a new procurement system, based not only on the financial cost of maintenance operations but also on CO_{2eq} emission, has been introduced. In three years, it has already led to a 30% reduction of CO_{2eq} emissions in maintenance projects. In addition, an analytical pavement design and analysis system, built to consider the local conditions (available materials, traffic loads, climate), will soon juxtaposed to today's guidelines based on empirical methods. It will facilitate not only the use of customized solutions but also the prediction of the pavement service life.

Through the introduction of more flexible and performance-oriented procurement and design systems, the aim is to increase the consultants and contractors' freedom in choosing the right solution, as far as the environmental and economic impact are balanced with the expected service life; the final purpose being encouraging the technological advancement needed to achieve the common climatic goals. This paper intents therefore to evaluate the progress and consequences of the Norwegian pavement sector's strategy for a more sustainable infrastructure.

Keyword: Pavement design · Procurement · Service life · CO_{2eq}

1 Introduction

"*We must take care of what we have, improve where we can, and build new where we have to*" expresses the vision of the Norwegian Public Road Administration (NPRA) of contributing to the transition into a low-emission society [1]. It intuitively summarizes the progressive societal shift in the western countries from a consumerist prospective of resources abundance and constant growth, to a future premised on sufficiency and resiliency [2]. Encouraged by the international acknowledgment of the ongoing climatic change and the ambitious greenhouse gas emissions goals, it extends to any aspect of the country's society and economy, including the asphalt pavement sector.

After years of relatively limited and slowly implemented advancements, the emphasis on the reduction of greenhouse gas emissions has been the kickstart the pavement

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 754–760, 2025.
https://doi.org/10.1007/978-3-031-95284-5_105

industry needed to begin a small revolution leading to the flourishing of new technologies, materials and routines.

In Norway, the introduction of new technologies and materials was initially led by the larger asphalt companies and industry's associations, thanks to the possibility to focus on R&D and the availability of resources to implement internal changes. While their motivation might swing between improving EHS (environment, health and safety) and the strictly financial gains, the repercussions spread to the whole asphalt industry and led to a National Transport Plan encouraging technological advances and daring to think differently [3].

On the road owner side, the need to keep abreast with the industry and to contribute to the national emission target for 2030 triggered drastic changes in how pavements are designed, built, maintained, and rehabilitated. New tendering processes have been introduced both at national, county and municipality level, and a new design method is being developed to increase the contractors' and consultants' freedom in the choice of materials; to stimulate the use of low emission technologies and to overall increase the service life of pavements.

This paper will give an overview of how the Norwegian road owners (NPRA, counties and municipalities) are striving to reduce the environmental footprint of their infrastructure and develop a future-oriented pavement sector.

2 Procurement Process

Starting from 2018, the NPRA, together with other road owners and the Norwegian Contractors Association (Entreprenørforeningen - Bygg og Anlegg), has gradually introduced the use of Environmental Product Declarations (EPD) in pavement maintenance contracts. In just four years, the NPRA went from requiring delivering any available EPD to use CO_{2eq} weighting in almost 90% (24 of 27) of its contracts. Four of these using a combination of CO_{2eq} weighting and life-cycle costs. The implementation process, a detailed description of the framework for EPDs and how an EPD-calculator has been developed specifically for the paving industry can be found in [4].

The scope behind the introduction of the new tendering process, is to both reduce the emissions linked to pavement maintenance contracts and, at the same time, encourage the development and purchase of low emission technologies, materials and giving more freedom to the industry. The aim is to reduce the amount of emission linked to maintenance contracts by 65% compared to 2020 within 2030.

2.1 CO2eq Weighting and Life Cycle Costs

When presenting a bid for a paving contract, each bidder is required to attach an EPD, describing the product's environmental performance, to the monetary price. The values corresponding to the stages A1 to A5 (product and construction stages) are then used to determine the environmental cost of the product in terms of CO_{2eq}.

In tendering process, the bidder with the lowest CO2eq cost establishes a baseline. All other bidders, with higher emissions, will have a certain among NOK/kgCO_{2eq} added to the monetary price. Depending on the road owner, this amount varies between 5 and

20 NOK (≈ 0,5 to 2 €/kgCO_{2eq}). The adjusted bidding sum (original price plus price based on the emissions) will determine the winning contractor. At the end of the contract, the actual CO_{2eq} cost will be documented by the winning bidder.

In the following Table 1 are shown the results collected between 2020 and 2023 by three road owners: the NPRA that manages the national roads and two counties, Troendelag and Viken, that manage the county roads in the proximity of Trondheim and Oslo. The 2020 values correspond to a traditional tendering process based on the lowest price, while the following years saw the introduction of CO_{2eq} weighing in more and more processes. The results are therefore to be considered as an average value from both types of contracts for the years 2021 to 2023. The introduction of CO_{2eq} weighing in 2021 has led to a clear impact for the NPRA contracts with a consistent decrease of emission, 30% in three years, in accordance with increasing amounts of tendering processes based on the new criteria. The same conclusion cannot yet be drawn for the county roads. However, it is clear from the EPDs that the contractors are taking several initiatives to reduce their footprint. So far, particular focus has been put into the use of bio additives and recycled asphalt (to reduce the emission quota of the bituminous products), low temperature mixes, and in the use of more environmentally friendly energy sources such as wood chips.

Table 1. Amount of kgCO_{2eq}/tonn asphalt between 2020 and 2023 as provided by the contractors in the EPDs (A1 to A5); the measured values (a) and including the end-of-life stages, C1 to C4 (b). The data are provided by the NPRA and counties of Troendelag and Viken.

	2020	2021	2022	2023
NPRA	62	54	48	41 (49)b
Troendelag County	69	75	53	-
Viken County	-	32 (31)a	27 (31)a	-

2.2 Challenges and Future Plans

One of the main difficulties to evaluate the effect on the new tendering processes is in the data collection. This is due to the large amount of road owners in the country and municipal level and the internal communication challenges. The lack of data makes it difficult to evaluate the effect of the new tendering process in the asphalt sector on a national level. The introduction of routines and increasingly familiarity with the terminology will hopefully improve the data quality and quantity.

As visible in Table 1 there are discrepancies between the declared and measured emissions. This is being partially solved by introducing a bonus/penalty system where, when the effective CO_{2eq} differs by more than 5% from the declared one a bonus (5 NOK/kgCO_{2eq} for lower total emissions) or a penalty (10 NOK/kg CO_{2eq} for higher total emissions) is triggered [4]. Nevertheless, there is still a possibility for a contractor to exploit the system, giving a lower bid if they determine the profit from the project can outweigh the penalty, especially in areas where the market does not allow for strong competition. In these cases, the road owners are considering the possibility of introducing a maximum amount of acceptable kgCO_{2eq}/tonn asphalt, over which the contract will not be assigned.

The next steps, already initiated by the NPRA, are the extension of the CO2eq evaluation to the C1-C4 end of life stages and the introduction of the pavement service life in the tendering process to incentive the production of better mixes. In this case the adjusted bidding sum is divided by the expected service life and the final price per year determines the winner.

3 Analytical Pavement Design and Analysis System

In Norway, pavement design is currently based on the N200 design guidelines [5]. An empirical design system developed by the NPRA in the 60ies. The system, based on material requirements and design tables/graphs, considers boundary conditions such as type of underground and traffic volume and partially taking into account local climate, traffic projections and material availability.

The current system is somehow straightforward but offers limited freedom for pavement design and does not take advantage of the local conditions and material to optimize the road structure. The advent of among others new non-regulated materials and technologies, emission requirements and leaner budgets have exposed the need for a better design tool able to customize and optimize a pavement structure based on the local conditions.

3.1 The VegDim Project

In 2018 the NPRA started an ambitious R&D project, VegDim, with the goal of developing and implementing an analytical pavement design and analysis system. The result is the ERAPave PP program (Elastic Response Analysis of Pavements – Performance Predictions) in collaboration with the Swedish Transport Administration. The program is based on a response and a performance component that calculates the stresses and strains induced in the pavement structures due to traffic loading under the local climate conditions and predicts the pavement degradation as a function of time [6].

A large amount of construction and underground materials commonly used in Norway, have been tested to determine their response to induced stress and strains due to traffic and climatic loading. This information has been used to compile a material database available to all users. During the design process, this information will be combined will the available boundary conditions to determine the pavement service life according to the current regulations. A detailed description of the project can be found in [7, 8].

Although the program is being developed by the NPRA, it can, as the N200 design guidelines, be used by any road owner in Norway.

3.2 Challenges and Future Impact

While a working version is already available [6], the NPRA is expected to officially launch the Norwegian adaptation of ERAPave PP, as a part of its design methodology, at the end 2024. The tool will then be available for all road owners, consultants and industry, and will allow a better customization of the road structure based on the local conditions and available materials. It will help optimize the pavement structure, increase quality, accuracy and reliability, and provide long term reduction of financial and environmental costs [9].

On the road owner side, the system will allow for better maintenance and rehabilitation planning. ERAPave PP will be able to: generate degradation models for both new and existing pavements with known construction allowing for a long-term maintenance planning and resources optimization; create documentation of the user's choices and resulting consequences for future use and contribute to a conscious use of the resources. The users will be able to quickly create several design options for each section to analyze in terms of cost, resource use, service life and so on, and in the future, to create a proprietary material library.

However, given the complexity of the system, the introduction of ERAPave PP will generate several challenges for the NPRA, starting from establishing how and who will have the authority to submit and to approve the designs.

The introduction of a new system, based on models cryptic for many, could trigger insecurity in the end-user due to lack of trust in the quality and reliability of the results. During the last sixty years the industry has followed the N200 guidelines, browsing from table to graph to design an approved pavement structure based on empirical and cemented knowledge. The trustworthiness of ERAPave PP will be a critical factor for determining its success. To smoothen its implementation, the project group has already investigated the challenges encountered in USA and Sweden by MEPDG and PMS Objekt respectively. Validation of the results, guidelines updated according to the new design methodology and knowledge have been identified as important elements to look after [10]. The NPRA has started a series of seminars to gradually introduce the new design method to the larger audience, focusing on the background, data validation and implementation plan. In addition, an IT team has taken the task of rendering the tool user friendly to help ensure increased buy-in and adoption.

A deep knowledge about mechanistic-empirical design and understanding of ERAPave PP's approach will be necessary to verify the quality of the input data, understand the results and introduce proprietary materials. The NPRA will have to, in collaboration with education institutes, organize courses in advanced pavement design for professionals in both road owners, consulting and construction companies for a general knowledge update.

Potential new materials will require extended testing with equipment generally not available outside research institutes. How larger and smaller asphalt producers will have access to it is still not clear.

It is difficult to determine how long it will take for a shift towards the new tool to take place and how it will be received. Large funds and resources have been invested in this project and the hope is that it will encourage better customized solutions to extend the pavement service life while still looking at the economy and the environment.

4 Conclusions

The Norwegian pavement sector is working hard to contribute to the 2030 climatic goals. While there are many obstacles between today and its success, it has so far been clear that both road owners, consulting and construction companies are willing to collaborate and are daring to make big changes in an industry that has been so far advancing at a slow pace.

During the last three years, road owners and contractors have collaborated to reduce the CO_{2eq} emissions in the product and transport stage of paving already up to 30% compared to 2020. The expectation is to reach a CO_{2eq} value of about 20 kg/tonn asphalt. The introduction of the pavement service life among the awarding criteria will be crucial to achieve this goal and to stimulate the consultants and contractors to plan and design for longer lifetime. Central in its evaluation will be the soon to be launched analytic design and analysis system.

Introducing these new tools will help professionals in all positions make conscious choices where both the now and the future are taken into account.

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Non-Contact Measurements of Wind Turbine Blades Repurposed as Pedestrian Bridges

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Abstract. Decommissioned wind turbine blades can get a second structural life through implementation in other sectors, contributing to the circular economy. This avoids an increase in landfill and ensures sustainable construction. The use of wind turbine blades at the end of their lifetime as a pedestrian bridge is one such example. However, assessment of such structures is complex due to the age, repurposing and the new requirements of performance from these structures. In this paper, we demonstrate how Short-Wave Infra-Red scanning Laser Doppler Vibrometry (SWIR-LDV) can rapidly assess these repurposed blades in terms of their responses, by carrying out modal analyses. To demonstrate this, a repurposed wind turbine blade currently being used as a pedestrian bridge in Cork is monitored. The results indicate that it is possible to rapidly assess modal estimates, and consequently the condition of the blade via non-contact measurements. This testing method can be particularly important in terms of new and rapid assessment methods of such structures with a complex lifetime history and evolutions of stress, fatigue and material characteristics, leading to safe design and assessment of their re-use.

Keywords: Bridge · Non-Contact · pedestrian · structural health monitoring · Laser Doppler Vibrometry · Wind Turbine Blades · repurposing · sustainability

1 Introduction

The use of repurposed structures is an important aspect of sustainable construction. While the importance of such usage is convincing, the safety and serviceability criteria and condition of such structures are less investigated. Benchmarks and demonstrative evidence can bridge this gap and establish best practice guidelines and recommendations, which can eventually create a pathway towards standardization. One such important area of application is the repurposing of end of life wind turbine blades [1]. With the rise of renewable energy demand and interest around the world, the manufacturing of

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 761–767, 2025.
https://doi.org/10.1007/978-3-031-95284-5_106

wind turbine blades has increased exponentially. This essentially also means that the possibility of such blades at the end of their lifetime becoming landfill is a major issue to tackle. Several first generation wind farms are now coming to the end of their lifetime and consequently, this is a problem that requires attention. An interesting proposition around re-use of such blades [2] has been in the form of using them as general furniture or architecture and also in a more structural sense in the form of pedestrian and cyclist bridges [3]. While the spans are shorter for such bridges and residual fatigue effects can be neglected based on the levels of stresses over the lifetime, there is inadequate understanding and information about residual capacity, degradation and the rates of the same [4]. Such uncertainty directly impact the lifetime performance criteria from serviceability and even from the point of view of safety. Under such circumstances, for a re-use sector of wind turbine blades to be popular at the end of their lifetime, techniques of assessing them around their structural reuse must be validated.

This paper directly addresses this issue and carries out non-contact rapid measurements with Laser Doppler Vibrometry [5, 6] and connects it with wireless accelerometer results. The work instruments and measures an actual pedestrian bridge in Ireland made out of end of life wind turbine blade and investigates its vibration responses and some of the modal parameters. The comparison provides an idea of the consistency, repeatability, opportunities and challenges for such a structure. It can lead to guidance of sensor placement, measurement strategies, rapid detection and model updating procedures, including investigation of novel artificial intelligence applications and digital twinning [7, 8].

2 Experimental Details

2.1 Blade Bridge

The Blade Bridge, a first in Ireland and one of the few globally, is a pedestrian footbridge traversing a small river on the Midleton-Youghal Greenway Co. Cork, Ireland and is constructed using two recycled wind turbine blades (Nordex N29 turbine, 13.4 m original length), acting as bridge girders on either side of the bridge (Fig. 1).

Fig. 1. Blade Bridge, Co.Cork, Ireland used for rapid assessment with Laser Doppler Vibrometry. The blade length is 11 m, the bridge span is 5 m and the maximum chord is ~1 m.

2.2 Instrumentation and Measurement

One of the turbine-blade girders of this symmetric bridge is measured (Fig. 2). Accelerometers were securely placed at 1/4, 1/2 and 3/4 span, sampling at 512 Hz for 1 h. The accelerometers used in this thesis are LORD G-Link3D piezoelectric wireless ones with rugged removable plastic covering and a base allowing for easy fixture to magnetic surfaces. The accelerometers were connected to a laptop via a Wi-Fi USB base station and corrected for drift. A multi-point infra-red scanning OptoMet Laser Doppler Vibrometer (LDV) was set up 9.7 m from the blade, on a bank near the bridge with a dense mesh of 27 scanning points were considered on the surface of the turbine blade sampling (Fig. 3) at 1024 Hz with a spectral resolution of 0.5 Hz. Speckle noise was present for some of the points of the mesh. Excitation of the bridge was from ambient wind.

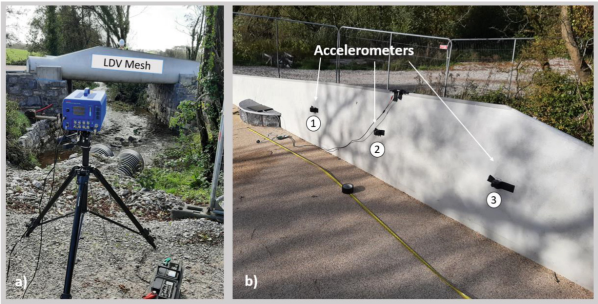

Fig. 2. Instrumentation and Measurement of Blade Bridge with (a) Multi-Point Short-Wave Infra-Red Laser Doppler Vibrometer and (b) Wireless 3D Accelerometers.

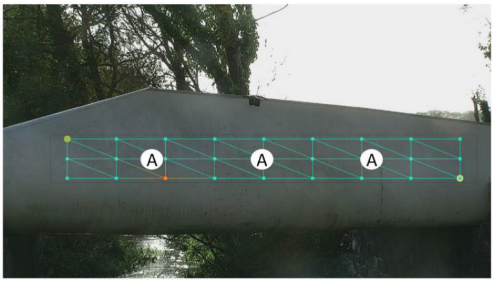

Fig. 3. Measurement mesh of Laser Doppler Vibrometer on one of the Blade Bridge girders repurposed from an end of life wind turbine blade.

The effects of speckle noise in terms of magnitude is summarized in Table 1. Derived values of acceleration from LDV measurements are compared with direct acceleration measurements in terms of Root mean square magnitudes. The LDV points in Table 1 should be compared based on whether there are speckle effects (marked by an asterisk) or not. The small variances are not just due to variability in the devices but rather from the fact that wind conditions were variable during the time. The overall orders of magnitudes match well but the errors are higher for lower acceleration magnitudes.

Table 1. Speckle noise (asterisk) effect of LDV for accelerometer locations (AL), g = 9.91 m/s^2

AL1 (average RMS = 0.0018g)	**RMS acceleration m/s^2 x g**
LDV Point 1*	0.0203
LDV Point 2*	0.0196
LDV Point 3	0.0022
AL2 (average RMS = 0.0035g)	**RMS acceleration m/s^2 x g**
LDV Point 4	0.0042
LDV Point 5	0.0017
LDV Point 6	0.0013
Mean of all LDV Points	**0.0024**
AL3 (average RMS = 0.0006g)	**RMS acceleration m/s2 x g**
LDV Point 7	0.0012
LDV Point 8*	0.0093
LDV Point 9*	0.1206

3 Results

3.1 Modal Estimates with LDV

Natural frequencies were determined simple by peak picking from the first singular values of the power spectral density matrix. Figure 4 compares this using a PSD matrix with all 27 points, as well as using one which includes only the 17 points deemed to be unaffected by speckle noise.

The effects of speckle noise is evident, introducing artificial frequency peaks unrelated to structural dynamics and also masking natural frequencies. The first natural frequency is likely near 10.5 Hz. However, the spectral resolution was 0.5 Hz and the real value is somewhere between 10 Hz and 11 Hz. There is also a significant peak at 105.0 Hz, as well close peaks at 61.5 Hz and 73.0 Hz. It is therefore likely that there is another natural frequency around 105 Hz, and possibly the two around 61.5 Hz and 73.0 Hz link to off the plane modes. Long term measurements can validate these further. A consistent mode shape in real-time was difficult to achieve due to lack of synchronization of the points.

3.2 Modal Estimates with Accelerometers

The accelerometers pose some challenge in terms of mounting and subsequent trend over time which has to be corrected for. This problem around instrumentation and measurement makes the non-contact LDV measurement more attractive and rapid. Figure 5

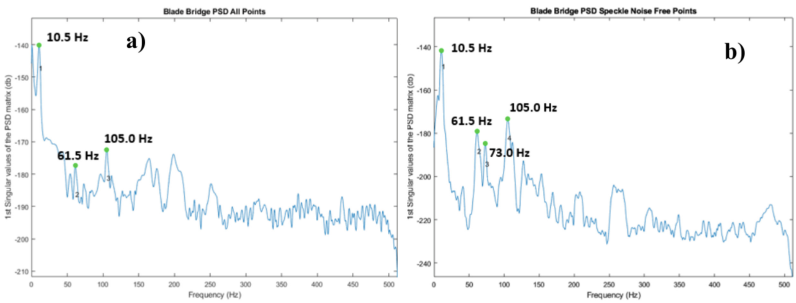

Fig. 4. Power Spectral Density estimate of blade bridge for points (a) affected by speckle noise and (b) unaffected by speckle noise for non-contact measurements.

shows that the in the singular value decomposition plot is significantly more noisy than that obtained from LDV measurements. The small frequency peaks at approximately 65 Hz, 73 Hz and 107 Hz may correspond natural frequencies of the turbine blade girder and they overall align with those obtained from LDV. The accelerometers were unable to measure what it likely the first natural frequency close to 10.5 Hz.

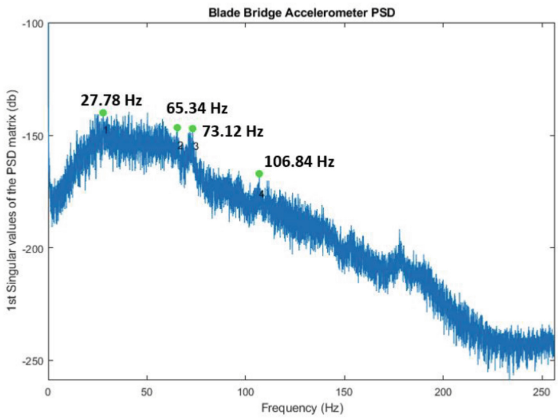

Fig. 5. Power Spectral Density estimate of blade bridge for accelerometer measurements.

4 Conclusions

This paper provided a rapid assessment of a full scale bridge of an end of life wind turbine blade repurposed as a pedestrian bridge. A comparison of non-contact measurement between multi-point short-wave infra-red Laser Doppler Vibrometry and wireless 3D accelerometers indicate that there such rapid assessments can be particularly important in terms of obtaining modal parameters and kinematic responses, which in turn are linked to the current state of the structure and its lifetime performance metrics. While non-contact LDV measurement was observed to be easier and more competitive, the challenges of handling speckle noise and uncertainties in excitation forces were observed, as well as the challenge obtaining live modeshapes in a reasonable manner. Accelerometer measurements were observed to be more noisy and with the challenge of mounting. With reasonable models and updating possibilities, such rapid non-contact techniques of measurement can not only be important in assessing lifetime performance of wind turbine blades repurposed as structural elements after their useful life on a turbine, but they can also be critical in establishing a pathway towards guidelines, recommendations and standardization of such structural repurposing.

Acknowledgments. The authors would like to acknowledge Sustainable Energy Authority of Ireland (SEAI) Remotwind project RDD/613, WindLederr Project RDD/601, Science Foundation Ireland (SFI) funded NexSys project 21/SPP/3756, MaREI centre RC2302_2, TraIn project NCF 22/NCF/FD/10995, EirBlade 22/NCF/EI/11163.

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A Contribution for a Sustainable, Resilient Road Infrastructure Management from Brisa, a Portuguese Road Concessionaire

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Abstract. Nowadays, there are increasingly efforts to introduce an economy based on circularity principles, but there is still a gap between the intentions and the actual measures to achieve it. In Portugal, reclaimed asphalt is generally used as granular material for unbound road layers or reused mainly as asphalt mix in the municipal road network, instead of reusing this premium material in new asphalt mixes for medium/heavy traffic, mainly due to the lack of knowledge on how to use these materials without compromising the performance or durability of the pavement.

The purpose of this study is therefore to evaluate the technological suitability of using two different rejuvenator additives (rejuvenator solid additive and terminal blend bitumen with rejuvenating additive) for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures for motorway surface courses. To achieve this objective, three gap graded asphalt mixtures (one of reference) for surface course were produced with 20% highly aged reclaimed asphalt milled from Brisa's motorway network. The results show that asphalt mixtures with reclaimed asphalt had better performance (water sensitivity, resistance to permanent deformation) and similar surface properties compared to reference asphalt mixture (without RA), regardless of the rejuvenator additive used.

Further studies will consider pavement monitoring the asphalt mixtures studied as well as mixtures with other rejuvenator additives in order to expand the possibilities of using reclaimed asphalt in Portugal.

Keywords: Road pavements · Circular economy · Resilient infrastructure

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 768–774, 2025.
https://doi.org/10.1007/978-3-031-95284-5_107

1 Introduction

Nowadays, there are increasingly efforts to introduce an economy based on circularity principles, but in some countries there is still a gap between the intentions and the actual measures to make it happen. Reclaimed asphalt (RA) generated by road maintenance is equivalent to about 850 million tonnes per year in Europe, the United States and China combined [1, 2].

According to the European Asphalt Pavement Association (Europe) [3] and the National Asphalt Pavement Association (United States) [4], almost all reclaimed asphalt is reused\recycled for the construction and maintenance of new roads (96% and 99% respectively). Looking at these figures in detail, we see that in the United States, of the 99%, only about 4% of the reclaimed asphalt is recycled for such as granular material for unbound road layers and only 0.1% ends up in a landfill. In Europe, the approach is slightly different, with the use of asphalt recycled as granular material for unbound road layers increasing to an average of 20% (from 0% in Croatia to an overwhelming 99% in Turkey) and 4% still ending up in landfill (from 0% in countries such as Austria, France, Germany, Hungary, Norway, Slovakia, Spain and Turkey to a remarkable 53% in Croatia).

As Europe has a consolidated road network, most of the reclaimed asphalt comes from maintenance/milling of surface courses, which have the scarcest aggregates, highest quality and therefore most expensive material for a road pavement. Landfilling these premium materials or using them as unbound materials whose properties are not so strict and not taking advantage of aged bitumen surrounding the aggregates is a luxurious prospect and shows the enormous effort needed to put us on the path of responsible valorisation of these materials, which means reusing them in surface course where they belong.

According to [3], no figures are given for Portugal, and the reality is perhaps not so different from Turkey or Croatia. In general, the reclaimed asphalt is used as granular material for unbound road layers or reused mainly as asphalt mix in the municipal road network, where the properties are not as important as in the national or motorway network, so the waste of a first-class material remains. Several factors lead to this reality, but the most important is probably the lack of openness of road concessionaires, as there are no specifications that allow the reuse of this type of material in new asphalt mixes for medium/heavy traffic due to the lack of knowledge on the use of these materials without compromising the performance or durability of the pavement.

Brisa has committed to the goal of achieving carbon neutrality by 2040 and to the promotion of circularity on the assets under its management (responsible consumption and production), and one of the steps towards that goal is maximizing the reuse of RA in surface courses, tackling issues as production and construction.

To achieve this goal, the ongoing study on new materials [5, 6] in this manuscript evaluates the technological suitability of two rejuvenator additives (rejuvenator additive and terminal blend bitumen with rejuvenating additive) for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures (gap graded asphalt mixes with 20% reclaimed asphalt (according to current limitations in Portuguese asphalt plant production) from an existing surface course in Brisa's motorway network) for motorway surface courses. The asphalt mixtures performance evaluation considered water sensitivity, resistance to permanent deformation and surface properties.

2 Experimental Programme

An experimental programme was carried out to evaluate the technological suitability of two rejuvenator additives for use with highly aged reclaimed asphalt (RA) in the production of new asphalt mixtures for motorway surface courses. The additives used were:

- Pelletized blend of 50% cellulose fibres (type Arbocel ZZ 8-1) and 50% of rejuvenator (cylindrical pellets of type Viatop plus RC, supplied by JRS).
- Terminal blend bitumen with rejuvenating additive (Elaster BM3-C Re-gener, supplied by CEPSA).

The RA (see Table 1 for properties) was obtained from porous asphalt mixtures milled from 17-year-old surface courses of the A3 motorway in northern Portugal (Brisa's motorway network). The reclaimed asphalt used corresponds to the coarser-grained fraction (RA 8/16 mm) obtained after grinding the milled aged asphalt mixtures. In addition Table 1 also shows the characterization of the base bitumen (PMB 45/80-65) without/with rejuvenator additives plus RA after recovery of the bitumen in the asphalt mixtures (centrifugation, EN 12697-1).

Table 1. Base bitumen and reclaimed asphalt characterization.

RA visual aspect	Properties	Base bitumen	Bitumen in RA without/with rejuvenator additives		
		PMB 45/80-65	No additive	Viatop RC	Regener
	Bitumen content (%)	-	3.3	-	-
	Penetration (0.1 mm)	49	6	36	36
	Softening temperature (°C)	68.0	93.0	69.6	69.0
	Elastic recovery (%)	87.3	-	-	82.8

Table 1 shows that the existing bitumen in the reclaimed asphalt has very low penetration values, requiring the use of rejuvenator additives or soft polymer modified bitumen in the production of the new asphalt mixtures. As expected, the addition of Viatop RC or Regener increased the penetration and softening temperature of the recovered bitumen (centrifugation, EN 12697-1), reducing the brittleness of the bitumen in the asphalt mixture with RA. With both additives, the softening temperature could be brought to a similar value as for the base bitumen (PMB 45/80-65).

The asphalt mixtures used in the study are listed in Table 2. They consist of virgin aggregates (granite 10/16, 4/12, 0/6 mm and limestone, filler) and reclaimed asphalt (granite, 8/16 mm). The base bitumen is a polymer modified bitumen classified as PMB 45/80-65 (commonly used in Brisa's motorway network) without/with rejuvenator additives.

Table 2. Asphalt mixtures studied.

AC 14 surf ID	Aggregate nature	RAP		Binder type	Binder content (%)		Rejuvenator	
		Fraction	Content (%)		Virgin	RAP	Type	Content (%)
M1-REF	Granite	-	-	PMB 45/80–65	5.0[1]	-	-	-
M1.1		8/16 mm	20		4.7	0.3[1]	Viatop RC	1.5
M1.2							Regener	-[2]

(1) optimum bitumen content; (2) confidential information.

The performance evaluation of the asphalt mixtures considers the assessment of: Marshall properties according to EN 12697-34 at 60 °C after conditioning the specimens at 60 °C for 40 min; water sensitivity according to EN 12697-12 (method A) at a test temperature of 15 °C after conditioning in air at 20 °C and vacuum in water at 40 °C for 72 h (dry and wet specimens respectively). For Marshall and water sensitivity, the cylindrical specimens were compacted with a Marshall compactor with 50 strokes on each side. Resistance to permanent deformation was evaluated according to EN 12697-24 (air method, 60 °C with 10000 cycles). In addition, the macrotexture depth of the asphalt mix surface was evaluated using the volumetric patch method on test specimens to assess resistance to permanent deformation in accordance with EN 13036-1.

3 Results and Discussion

Figures 1, 2, 3 and 4 show the Marshall properties, water sensitivity, resistance to permanent deformation and macrotexture depth of the asphalt mixtures studied (AC14 surf) without/with reclaimed asphalt plus rejuvenator additive for the optimum bitumen content.

As expected, the results in Fig. 1 show a reduction in the Marshall stability (S) of asphalt mixtures with rejuvenator additives. The Marshall flow behavior (F) also shows a reduction compared to the reference asphalt mixture and a slight increase in the Marshall quotient (Q), indicating that asphalt mixtures with rejuvenators tend to be more flexible than the reference mixture (without RA), despite the highly aged reclaimed asphalt used, without compromising resistance to permanent deformation. These results are confirmed in Fig. 3 by the slight reduction in permanent deformation (rut depth and wheel tracking slope) for asphalt mixtures with reclaimed asphalt and rejuvenators (M1.1, Viatop RC and M1.2, Regener) compared to the reference asphalt mixture (M1-REF). Asphalt mixtures water sensitivity is sensitive to the use of reclaimed asphalt

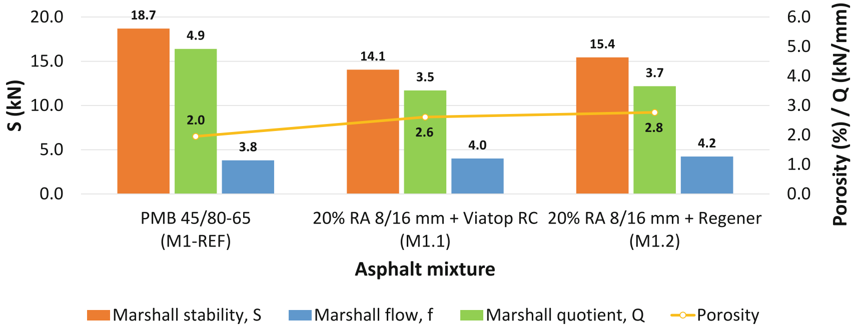

Fig. 1. Marshall results.

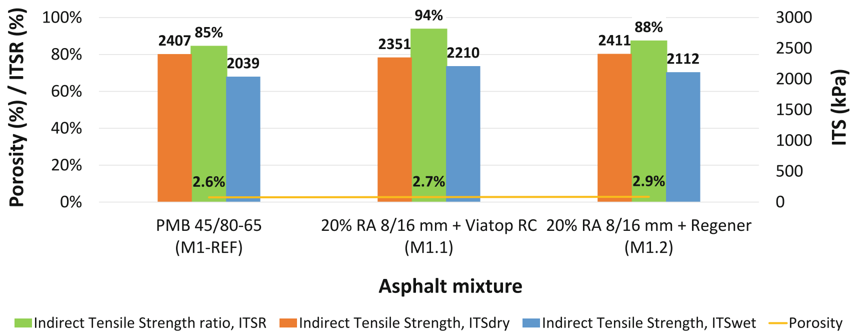

Fig. 2. Water sensitivity results.

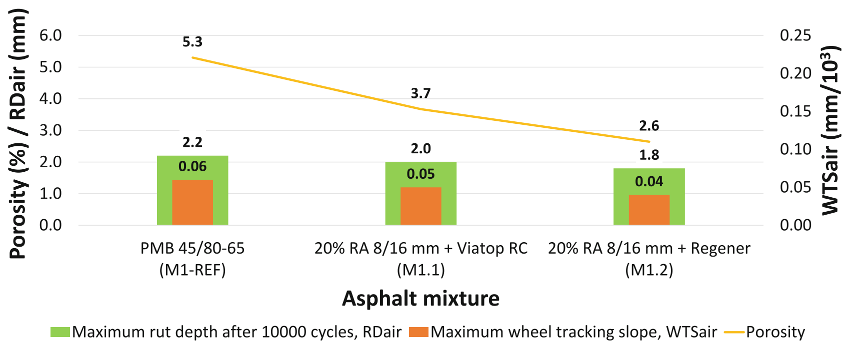

Fig. 3. Permanent deformation results.

(e.g. due to possible insufficient blending between aged and virgin bitumen [7]), but the rejuvenator additives used were able to compensate (M1.2, Regener) and even reduce (M1.1, Viatop RC) the water sensitivity of the asphalt mix, as shown in Fig. 2, without affecting or even slightly increasing the indirect tensile strength (ITS) of the wet and dry test specimens compared to the reference asphalt mixture. As far as the surface

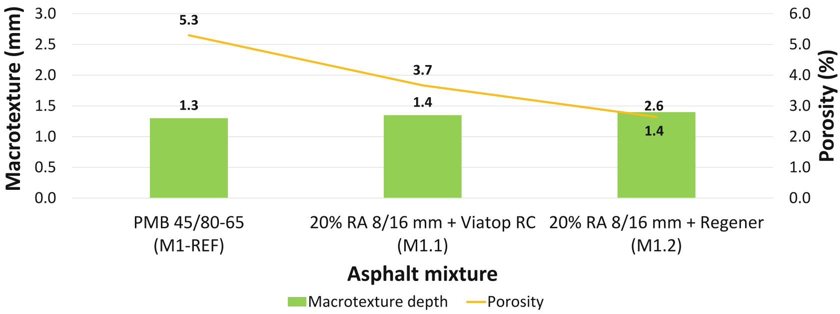

Fig. 4. Surface properties results.

properties are concerned, Fig. 4 shows that the use of reclaimed asphalt or rejuvenator additives has no influence on the surface properties compared to the reference asphalt mixture.

4 Conclusions

Overall, the use of reclaimed asphalt leads to a reduction in the consumption of virgin aggregates and virgin bitumen: promoting a circular economy with environmental benefits and potential economic advantages. It has been shown that the additives used can improve the behaviour of the studied asphalt mixtures with reclaimed asphalt, raising the bar for further studies on higher contents of reclaimed asphalt. However, proper laboratory characterisation is required to correctly determine the type and content of rejuvenator additives. Further steps need to be taken to increase knowledge in Portugal, while in parallel further specifications and proper management of reclaimed asphalt need to be developed.

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Methodologies for Economic Assessment of Rail Technical Innovations: Challenges and New Perspectives

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Abstract. The objectives of the Shift2Rail / Europe's Rail research programme include the doubling of capacity and halving of life-cycle costs. If these could be achieved it would make a substantial contribution to the competitiveness of rail transport. A key challenge in rail technical research lies in the selection of innovations that are likely to achieve a positive business case, as well as a positive financial case for individual actors in the system. However, there are number of significant challenges in operationalising methods to assess schemes such as Cost Benefit Analysis (CBA) in order to deliver useful information to guide rail technology selection. These include obtaining data on key aspects of costs to populate the base case scenario and translating results from engineering testing into cost impacts in the CBA. This paper uses examples from projects undertaken under the Shift2Rail / Europe's Rail research programme to highlight areas of best / novel practice and sets out ideas for future development.

Keyword: life cycle costs · statistical cost models · valuation of benefits

1 Introduction

EU transport policy as set out in, for example, the 2011 European White Paper, is predicated on rail becoming the main means of medium distance passenger transport and of long distance freight transport. This policy was reiterated as part of the EU Green Deal (2019). A number of policies are in place with the aim of achieving this shift, including innovations in rail transport driven by a major research programme (Shift2Rail and now Europe's Rail). If innovation were able to achieve the objectives of the Shift2Rail programme, including doubling capacity and halving life cycle costs, it would make an enormous contribution to the competitiveness of rail transport.

However, a key challenge in rail technical research lies in the selection of innovations that are likely to achieve a positive business case, as well as a positive financial case for individual actors in the system. Whilst Key Performance Indicators (KPIs) can be set out and techniques such as cost benefit analysis (CBA) are well known in principle, there are a number of significant challenges in operationalising these approaches in order to deliver useful information to guide rail technology selection.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 775–781, 2025.
https://doi.org/10.1007/978-3-031-95284-5_108

Obtaining the data on key aspects of costs to populate the base case (or AS IS or Do-MINIMUM) scenario is often problematic. Whilst engineering / simulation models can be used to understand the impact that technologies might have on, for example, maintenance intervals, the understanding / modelling to translate these changes into cost impacts (bearing in mind that the research may focus on a single component of an infrastructure system of vehicle) is much more of a challenge. Where scheduled maintenance covers a range of components, extending the life on one component may have little benefit without progress on the life of the remaining components. Further, whilst wider benefits such as impacts on reliability are expected these are notoriously difficult both to quantify and then value.

This paper uses examples from projects undertaken under the Shift2Rail / Europe's Rail research programme to highlight areas of best / novel practice, particularly focusing on how statistical methods utilising real cost data can be used to understand cost drivers in rail, how CBA techniques can be applied to produce useful insights on the overall business case and the circumstances that drive a positive business case, and on how improvements in quality can be evaluated and more systematically incorporated into business case assessments. Finally, the paper calls for future work to generate cost and demand /quality side parameters and approaches in the form of a Business Case Assessment Handbook that can be used to assist business case evaluation of rail technical innovations in the future.

2 Methodology

One of the common approaches for assessing the economic impact of railway innovations on Shift2Rail projects is Cost Benefit Analysis (CBA). CBA analysis takes the perspective of overall society since it aims at accounting for every possible impact. For this reason, it can be referred to as a Social CBA. At the same time, it is important to identify the recipients of each cost and benefit. Therefore, CBA usually includes a stakeholder assessment, where each impact is associated to a specific agent in the economy. The two elements of the CBA can be summarised as follows: a socio-economic CBA, covering all affected parties (i.e. society); and, a financial CBA, analysing the impacts on each of the relevant stakeholders. Table 1 includes a generic description of impacts and groups that could be considered for railway projects.

Table 1. Social and Stakeholder CBA – Impacts Table by Group

IMs	Train Operators	End users	Third Parties
• Changes in costs and revenues	• Changes in costs and revenues	• Change in costs and benefits for passengers and freight users (e.g. improvements frequency, etc.)	• Environmental externalities • Government: grant / subsidy • Residents • Wider economy

To develop the CBA, the starting point is the definition of the baseline scenario, also called the Do-Minimum scenario. The baseline should represent the most likely situation of the railway line if the innovations are not applied (i.e. current context). Secondly, a Do-Something scenario should be defined precisely, e.g. as the situation of the railway line if one particular innovation is applied; and the impacts might vary substantially for different networks (e.g. high speed versus lightly used rural routes). A CBA recommends the implementation of an innovation or change of practice where its benefits outweigh its costs. The costs and benefits are estimated using standardised parameters set out by public bodies in their appraisal guidelines such as in the UK [1] and EU [2].

In the following section examples from Shift2Rail projects are used to highlight some of the challenges of applying CBA on rail projects and the novel practices which have been developed to negate them. See also [3, 4] for further details.

3 Results

In this section two projects (IN2ZONE and GEARBODIES) in the Shift2Rail programme are used as a locus to illustrate some of the challenges/best practice in undertaking the appraisal of rail projects (Sects. 3.1, 3.2 and 3.3). This is followed by suggestions for future work in this field (Sect. 3.4).

3.1 Scheduled Maintenance of Multiple Components

Part of the GEARBODIES project involved the development of innovations for the journal bearing elements on high-speed trains. The main expected impacts of the innovations were expected to emanate from Life Cycle Cost (LCC) reductions, associated with increased maintenance intervals. These impacts arise from the enhanced durability of the components which would allow them to be replaced less frequently.

To estimate the impact on LCC of the increased durability of a component it is not enough to consider only the maintenance schedule of the component itself. This is because an enhanced lifetime of one component may only provide a benefit if this can generate increased intervals between maintenance/replacement activities, which are often planned with respect to multiple components. To identify the interaction of the maintenance activities of different bogie components vehicle maintenance plans need to be considered. For commercial reasons it is difficult to obtain actual maintenance plans and an alternative approach was, therefore, used which was to develop an indicative maintenance plan. Through this process the components which have the shortest maintenance intervals and are therefore key in determining when bogie overhauls are undertaken were identified.

The indicative maintenance plan was established assuming that the timing of bogie overhauls is determined by the wheels as they are considered the bogie component with the shortest maintenance interval, i.e. not capable of reaching 1.65 Mkm (which is the current interval of the technology of interest, namely the journal bearing). This means that the lifetime of the wheels and, therefore, the timing of bogie overhauls is once every 1.5 Mkm. As it is the wheels that determine the frequency of bogie overhauls any LCC savings from an increase in the durability of journal bearings will be realised for the bearings only as the maintenance intervals of all other bogie components will not be affected. This also means that for LCC savings from the extension of maintenance intervals for journal bearings to be realised in practice the extension must be great enough to reach the next bogie overhaul.

The theoretical modelling undertaken suggests that a maintenance interval for journal bearings of close to 3 million km (3 Mkm) could be achieved but further testing is required to validate this. The estimated LCC saving over a 30-year appraisal period of extending the maintenance interval of the journal bearings from one bogie overhaul (i.e. 1.5 Mkm) to every other overhaul (i.e. 3.0 Mkm) was 42.9%. It is important to note, however, that if a still substantial increase in the maintenance interval had been realised - but less than that required to reach the next bogie overhaul - then no LCC savings would be realised. This highlights that in future research the targets for the length of maintenance intervals for components need to consider the impacts on other components and not only the component itself. This represents a significant step up in complexity in terms of modelling but is necessary to be able to make more definitive statements about the costs and benefits of enhancing the durability of specific components.

3.2 Translation of Engineering Tests Outputs to CBA Inputs

Another constituent of the GEARBODIES study was the development of new elastomeric materials which are used for the bushes in the swing arm on high-speed bogies. As with the journal bearing innovations discussed in Sect. 3.1 the main expected benefit of the new materials was expected to be LCC savings arising from the extension of maintenance intervals resulting from increased durability.

The results from the mechanical tests on the new polymers developed for the bushes suggested that an increase in durability was achieved. The results showed that the new polymers led to an improvement in tear strength (150%), tensile strength (28%), elongation at break (21%) and hardness (6%). While these engineering tests suggested that durability had increased they could not confirm if it would be sufficient to allow an increase in the maintenance interval (from once every four bogie overhauls currently) and further testing is required to confirm this.

The lack of clear and robust results on the durability of the new polymers meant that the impact assessment could only give an indication of the potential benefits of extending maintenance intervals. The LCC savings over a 30-year appraisal period of extending the maintenance interval from every four bogie overhauls (i.e. 6 million km) to every five (i.e. 7.5 million km) were estimated at 24.3%. If the increase in the maintenance interval was less than required to reach the next bogie overhaul then no LCC savings would be realised in practice as the bushes would continue to be replaced every 6 million km. This undertaking of this analysis highlights that for the purposes of impact assessments in future projects it is important that engineering tests are designed to produce inputs which can be used in a CBA, which emphasizes early interaction between technical and economic research in technical rail research projects.

3.3 Utilisation of Statistical Methods to Understand Cost Drivers

The IN2ZONE study involved the design and development of innovations at transition zones which are the areas on railway lines adjacent to structures such as bridges and tunnels. In such locations greater track support is required to allow a smooth transition between regular track and the stiffer support conditions provided on structures. The sudden change in support conditions leads to increased track degradation which requires more frequency maintenance interventions at greater cost. In IN2ZONE prototype next generation transition zone solutions were developed which provide a step-change in track support conditions, leading to a reduction in maintenance interventions.

The benefit of a transition zone solution relies on its impact on the railway system's life-cycle cost and capability. A key challenge in rail technical analysis is obtaining good cost data at a disaggregate level for different assets and in different locations on the network and in turn how costs vary with different cost drivers. This can make it hard to establish a baseline scenario.

In IN2ZONE a cost model was used to generate information about maintenance which built on the approach utilised in the NeTIRail-INFRA project [5]. Let C represent maintenance cost per track km, Q is traffic per track km and X is a vector of infrastructure characteristics per track km – but importantly for our analysis includes the number of structures (bridges and tunnels) on the section (given that each structure will be associated with two transition zones). The cost model can be written as:

$$C = f(Q, \boldsymbol{X}) \tag{1}$$

The double-log specification was used which is common in the literature addressing rail infrastructure costs. Information about maintenance costs, the infrastructure characteristics, traffic as well as some maintenance activities was collected for an Infrastructure Manager in Europe.

The presence of tunnels and bridges on a rail section provides a first indication of the effect of transition zones on track maintenance costs. The results show a positive and statistically significant (at the 1 per cent level) impact of this variable on costs (parameter estimated of 0.131, which can be interpreted as an elasticity). This result indicates that, for example, increasing the number of structures on an average track section by 100 per cent would be expected to increase the track maintenance costs by up to about 13 percent according to the model. The results from the model were used to estimate that the annual extra cost per transition zone is €2,211.90 (2023 Prices). Since not only the transition zone, but also other parts of the structures may require maintenance, this number provides an upper limit for the impact on costs if the number of transition zones would change or if each zone could be reinforced.

3.4 Recommendations for Future Research

In addition to the examples outlined in the previous sections several other recommendations can be made for enhancing impact assessments based on those the authors have been engaged in the Shift2Rail programme. Firstly, there are a range of wider benefits of innovations for which valuation is challenging. For example, enhanced reliability is a common expected impact of rail innovations but is notoriously difficult both to quantify and then value (the former part, obtaining data on delays caused by different types of failure on different line types being the biggest challenge as values do exist in the literature for delays [6]). Secondly, although public bodies have standardized parameters to use in CBA such as discount rates, appraisal periods, etc. it would be constructive to establish a consistent set of cost and demand /quality side parameters and approaches. These could be brought together in the form of a Business Case Assessment Handbook that could be used to assist evaluation of rail technical innovations in the future.

4 Conclusion

In most (if not all) industries, technological innovations may improve efficiency and productivity and can make goods and services more accessible to all. However, an economic understanding of the implementation and impacts of technologies is necessary but non-trivial: it involves a series of challenges which have surprisingly received little attention in the literature.

Some of the challenges of business cases in the rail sector and novel approaches for alleviating them were illustrated in this paper using examples from the Shift2Rail programme. Obtaining data on key aspects of costs to populate the base case scenario is often problematic and statistical methods were outlined which can be used for utilising real cost data to understand cost drivers. Research into components often may focus on a single component but where scheduled maintenance covers a range of components, extending the life on one component may have little benefit without progress on the life of the remaining components. In this paper it was shown how the development of an indicative maintenance plan can allow an assessment of how an increase in the durability of a component is affected by the maintenance requirements of other components and, therefore, the extent to which LCC savings can be realized in practice. While the methods outlined in this paper can assist in enhancing impact assessments going forwards further work is needed to develop approaches for evaluating some of the commonly expected benefits of rail innovations such as reliability. In addition, the impact assessments of rail innovations would benefit from the development of a Business Case Handbook which contained a standardized set of parameters and approaches for business case evaluation; as well as improved disaggregate data to support decision making.

Acknowledgements. We would like to acknowledge the contributions of the partners of the GEARBODIES and IN2ZONE projects to the underlying work discussed in this paper.

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Material Supply of Urban Factories Using Circulation Hubs - An Analytical Comparison of the Logistical Effort

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Abstract. Climate change, the responsible use of natural resources, and continuous urbanization raise the question of how urban factories can be supplied more sustainably. The concept of an Urban Circulation Hub can provide a potential solution. An Urban Circulation Hub can meet the resource needs of urban production systems by specifically collecting suitable waste materials generated in urban areas and making them available as input or secondary raw materials. By establishing such a hub, originally unused waste material flows can be made accessible and usable. This paper focuses on the logistical effort of an Urban Circulation Hub, for which scenarios are compared and evaluated with a simulation in AnyLogic. The simulation is based on a case study of an eyewear factory in Sydney. The result shows that an Urban Circulation Hub can be a sustainable, resilient, and cost-effective alternative for raw material supply. However, this requires sufficiently recycling waste streams generated in the urban area.

Keywords: Urban Circulation Hub · Urban Factories · Simulation · Sustainable Development · Reverse Logistics · Circular Economy · Circulation Factory

1 Introduction

The pressure on natural resources to supply production systems for the manufacturing of products is becoming increasingly important due to their scarcity and connected environmental impacts. This scarcity raises the question of sustainable strategies to supply production sites towards circular or cascading material flows. Today, a high share of consumer goods is produced in globalized mass-production systems. On the one hand, this can allow exploiting effects of economies of scale. On the other hand, the concept of symbiotic material flows for smaller, decentralized manufacturing systems can lower environmental impacts associated with material and energy demand of industrial activities. This would allow the utilization of the output flows of waste, energy or by-products

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 782–788, 2025.
https://doi.org/10.1007/978-3-031-95284-5_109

from one company or consumers as input flows for another enterprise [1, 2]. However, due to technological and organizational barriers, symbiotic concepts are rarely implemented and can be found mostly in controlled environments such as industrial parks [3]. Urban areas in particular need to be considered as they have a high density of waste generation and product demand [4]. This is where the concept of the Urban Circulation Hub (UCH) needs to be discussed, as an UCH can supply the resource needs of urban production systems by collecting suitable waste materials generated in urban areas and providing these as input or secondary raw materials. The paper aims to compare the logistical effort of innovative UCH concepts based on scenarios.

2 Systematic Literature Review and Case-Study

In order to address the research topic of the material supply of Urban Factories using UCHs, a systematic literature review was conducted, based on the guidelines of Durach *et al.* [5]. The search query is *TITLTE-ABS-KEY (circular AND hub) OR (circular AND economy) OR (circulation AND factory) AND TITLE-ABS-KEY (urban) OR (urban AND production) AND TITLE-ABS-KEY (reverse AND logistics) OR (transport*) OR (logistics*).* After full-text analysis, 12 results emerged.

Most of the analyzed literature is of theoretical focus. Furthermore, it becomes apparent that some have an urban focus related to industrial symbiosis and only few have a logistical focus. The concept of industrial or especially urban symbiosis is defined by the fact that the generated waste, pollution and by-products of one production site are reused in other production sites. [6] Urban symbiosis describes the formation of a network for the physical exchange of waste and by-products within a city [1, 7–9], with or without further treatment or recycling processes [10]. The connection of industrial production sites and other resource sources or utilizations in urban area is called urban-industrial symbiosis and describes the idea of industrial symbiosis transferred to the city-factory-system [8, 9, 11, 12]. Another concept for the utilization of local waste to supply productions is the urban secondary raw material factory [10]. Genc *et al.* [3] presented the Circular Eco-Industrial Park as a place of the utilization of waste, but not in an urban context. Rickert *et al.* [13] describe the concept of the Circulation Factory. An UCH networks with other actors in the city-factory-system and sources material flows directly from other traders, thus saving transportation to landfills. This raises the need of taking a closer look at the material flows and analyzing the logistical effort. It turns out that there are studies on certain logistical aspects related to the circular economy and reverse urban logistics [2, 14], but none that address the logistical impacts based on a case study and using an agent-based simulation (ABS).

Following the outlined necessity of analyzing an UCH, a concept evaluation on different scenarios will be performed by conducting an ABS. In the context of logistics, ABS is an important tool that is widely used for decision support. The simulation methodology can compare an actual state with different scenarios (target states) to draw conclusions that can be transferred to reality [15]. Based on this, ABS is used to evaluate the impact on transport logistics activities due to the implementation of an UCH. For a structured approach, the VDI Guideline 3633 Part 1 is used [16].

The case study under investigation is based on the data of a life cycle assessment of a product from a manufacturer in Sydney, an eyeglass frame to be fitted with lenses. It is based on the scenario II from the study by Juraschek *et al.* [11], as baseline scenario.

To identify possible advantages and challenges of UCHs in terms of logistical efforts, the effects of supplying the production using an UCH are compared with conventional supply strategies. For this purpose, a baseline scenario 1-A of the actual supply to the factory is modeled. The further scenarios (Fig. 2) are then used to model the impact of supplying the factory from one, several, and many UCHs in Sydney.

2.1 Simulation Model

The software AnyLogic 8.8 is used to develop the simulation model. The simulation model uses discrete and agent-based modeling (Fig. 1) to map the process of the supply chain by interaction with each other. A main agent serves as a central instance. It links all agents with each other and contains central control elements and a geographic information system map. The routing for individual transports within and around Sydney is implemented using the interface to an online map service provided by AnyLogic. The connections of the agents are shown in the schematic overview in Fig. 1.

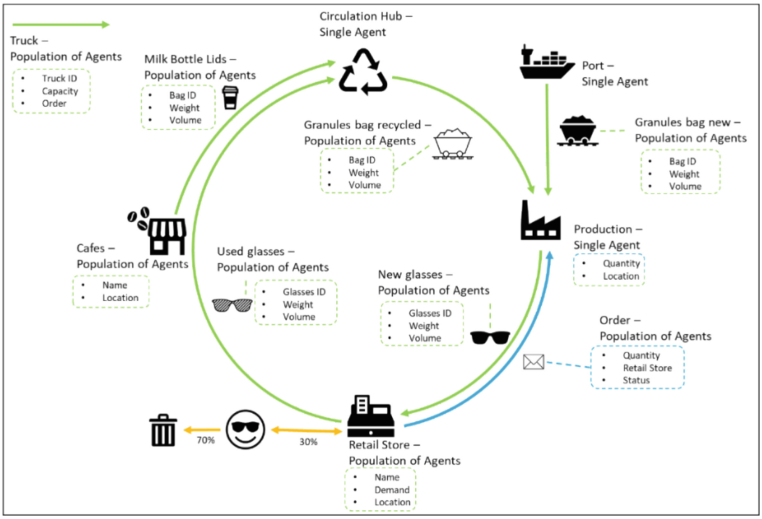

Fig. 1. Schematic representation of the circular process flows

The process begins with the production of the eyewear frames. The materials used are either virgin material (granule) delivered from Asia by ship or recycled materials, for which a share of 25% virgin material with 75% recycled material is set to ensure product quality. The transport of the virgin material is conducted by 40t trucks. Depending on the scenario, a differentiation is made between centralized and decentralized production in the individual retail stores. The frames will be transported by 7.5t trucks to the five retail stores as soon as they are finished. The order frequency depends on the respective stores, their demand, and the safety stock. When a new pair of glasses is sold, the customer can exchange old glasses for a new pair. The probability of such an event can be set individually in the simulation model. These used glasses are collected in the respective stores and then transported to the UCHs. Depending on the chosen scenario, the mode of this transport varies. In one scenario, the glasses are collected from the UCH by a truck via milk run; in another, they are collected after the delivery of new glasses. At the UCH, the eyeglass frames will be recycled. In addition to the glasses, milk bottle lids are recycled and collected in advance from the respective cafes.

2.2 Scenarios and Results

The simulation observation period was defined as one year. Stochastic effects influence the model due to customer demand shifts, initial inventory and safety stocks. This makes a transient phase necessary, which in this case study is six months and is defined by the Method of Welch [17]. Key performance indicators were defined to compare the logistic effort of the scenarios: tkm, number of transports, and kg CO_2 emissions based on averages per tkm by Mulholland *et al.* [18]. The results are subdivided by the vehicle types 7,5t and 40t. The following Fig. 2 presents the scenarios and results.

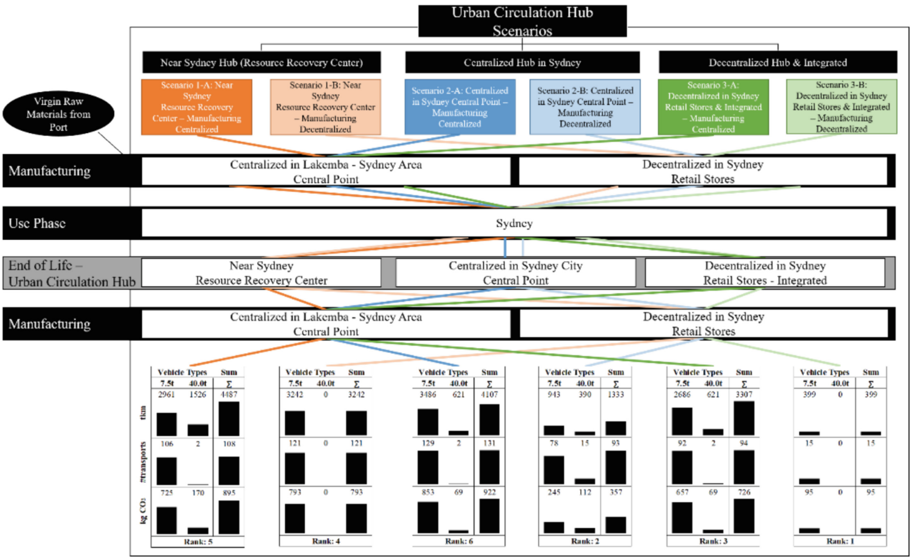

Fig. 2. Scenarios & Logistical Effort

The evaluation of the different scenarios shows that Scenario 3-B, where UCHs and retail stores are organized decentralized and integrated, represents the best results with a total of 95kg CO_2 emissions. This is caused by significantly lower transports. In contrast, in scenario 2-A, including a centralized production and recycling, the average CO_2 emissions determined per replication amount to 922kg CO_2, thus almost 10 times greater than in Scenario 3-B and representing the highest CO_2 emissions of all scenarios.

This is due to the increased transportation processes resulting from waste collection and the distribution of products to the retail stores. It can be seen that production and recycling within the city are preferable in terms of transport emissions. It seems logical, as the integrated UCH scenario or the centralized Circulation Hub scenario eliminate or minimize the corresponding milk runs to supply the retail stores. The main advantage of the UCH is that there is no need for transports, but the main challenge is to find a suitable urban location for the UCH and to cover the operating and construction costs.

3 Conclusion and Further Research

An UCH can meet the resource needs of urban production systems by specifically collecting suitable waste materials generated in urban areas and making them available as input or secondary raw materials. The location of such an UCH is either integrated into the decentralized urban production system or close to the corresponding retail stores. In the best scenario (3-B), the production systems, UCHs and retail stores are organized in a decentralized manner and integrated with each other, which leads to only a few transports. On the other hand, operating and construction costs of the production sites and UCHs can be higher per product output, as the establishment of smaller production units can possess negative economy of scale effects on processing efficiency. These should be compared with transport costs, emissions or the effects of the reduction of overproduction in future studies. Another approach to optimize transport and reduce CO_2 emissions would be to deliver the finished products to the retail stores and collect the secondary raw materials at the same time. Furthermore, in some countries there are legal hurdles to reuse secondary raw materials, which can be overcome by for instance establishing deposit systems. Finally, it should be noted that the operation of the UCHs in our case study is simple, as only a few types of raw materials are needed to produce the eyeglass frames. If many raw materials are used in a product, the processes and structure of the UCHs must also change, for example, the space requirement increases.

Acknowledgements. The research leading to the presented results has received funding from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) for the research project "Urban Factory II" (Grant no. 03EN3042B).

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Designing Low Energy Sustainable Asphalt Mixtures Based on Their Mechanical Properties and Performance Characteristics

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Abstract. The term "Sustainability" is a complex word to define. Focusing on the transportation sector as a structural infrastructure, more specifically on pavements, sustainability refers to the impacts on the environment, economy, and society at all stages, including material selection, design, and construction, as well as preservation strategies. The aim of this paper is to evaluate the sustainability of high RAP content asphalt mixes and the testing methodology involved in the determination of the key mechanical properties. Given that pavements are material intensive assets, a large focus in pavement sustainability to date has been on the use of recycled materials in road construction. The present study is part of wider research on the performance and durability of asphalt mixtures incorporating Reclaimed Asphalt Pavement (RAP).

Keyword: Sustainability · Recycling · Sustainable Pavement

1 Introduction

1.1 Sustainability Assessment

Within the past two decades, the asphalt paving industry has responded positively to increasing global concerns over shrinking natural resource reserves and worsening environmental conditions through the development and deployment of RAP and Warm Mix Asphalt (WMA) technologies (Tutu & Tuffour, 2016). In order to promote sustainable practices and to combat price increases, measures with sound sustainability credentials need to be widely implemented. Developing novel materials and technologies to integrate greener material, waste, and recycled materials into the production cycle of asphalt mixtures is a solution that improves both sustainability and cost-efficiency of the asphalt pavement industry. A sustainable pavement has to be economically, socially, and environmentally feasible at an acceptable level of risk over its design life. Practically, a sustainable pavement optimizes a range of performance indicators including cost, functionality, safety, local economic and human development, emissions, climate change and resource use, amongst others, which are measured by using a suite of assessment methodologies (Blaauw, et al., 2022). Pavements are engineered systems present

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 789–795, 2025.
https://doi.org/10.1007/978-3-031-95284-5_110

in every modern society, and they have significant environmental, economic, and social impacts. In an effort to promote more sustainable decisions regarding pavement design, construction and management, several pavement sustainability assessment tools have been developed (Plati, 2019).

Given that pavements are material intensive assets, a large focus in pavement sustainability has been on the use of recycled materials in road construction (Bryce, et al., 2017). A sustainable pavement can be defined as a pavement that supports long-life engineering reliability, with minimum environmental impact. The need to minimize the use of scarce primary resources is becoming more urgent in the pavement industry (Asres, et al., 2022). Thus, sustainable pavement design is based on some criteria, such as minimizing reliance on natural resources, reducing energy consumption and Greenhouse Gas Emissions (GHG) emissions, limiting air, water, and noise pollution, and improving health, safety, risk prevention, and user comfort (Plati, 2019).

1.2 Performance Based Design

One of the most topical research areas currently concerns the identification and improvement of technologies against climate change, environmental pollution, exploitation of natural resources, and the economic crisis (Daniel & Lachance, 2005). Of course, the field of road pavement engineering has also been involved in this battle. In recent years, themes of sustainability and circular economy have become the main keywords for scientists, administrations, designers, and constructors worldwide (Bochi, 2022). Utilizing recycled asphalt pavements (RAP) in pavement construction is widely accepted as a sustainable approach with significant economic and environmental benefits. RAP has been favoured over virgin materials in recent years for three main reasons: (1) crude oil and consequently asphalt binder cost increases, (2) scarcity of quality aggregates, and (3) increasing necessity for using sustainable materials in road pavements (Daniel & Lachance, 2005).

In the field of pavement engineering, the word "sustainability" can be related to several aspects, including the manufacture of road materials and their performance, the management of temperatures and emissions during road construction and service life, and analyses of the socio-economic and environmental impacts generated by the road infrastructures. This can also be achieved by increasing the performance of the materials against traffic loads and environmental factors, thus extending the durability of the whole pavement system (Bochi, 2022). Performance-based tests can be used to characterize asphalt mixtures regardless of materials and technologies in use, thus allowing the extension of pavement life cycle, cost savings and minimization of their environ-mental footprint (Zaumanis, et al., 2018). For the sustainability of the road pavement, temperature is a key factor not only during the service life of the infrastructure but also when the Hot Mix Asphalt (HMA) is produced. In fact, an incorrect management of the virgin aggregate, RAP, and bitumen temperatures at the mixing plant can give rise to excessive pollutant emissions and substandard performance of the HMA (Bochi, 2022).

In order to guarantee quality construction of asphalt pavements, effective specification is essential. Performance-oriented specifications, which adopt direct performance characteristics of pavements as the quality goals of the construction such as the performance-related specifications (PRS) and performance-based specifications (PBS), are gaining national popularity to overcome disadvantages of conventional QC/QA specifications (AASHTO, 2003).

2 Materials and Specimen Preparation

2.1 Materials

For this study, two mixtures were selected to be evaluated for their mechanical properties and fatigue performance. These mixtures incorporate two different percentages of RAP: 0% and 40%. A sustainable approach in asphalt pavement engineering should focus on materials, design methods, and technologies that can contribute to minimizing environmental impacts through a reduction in energy consumption and natural resources, while ensuring that all performance standards and requirements are met.

Bitumen is an essential part of the asphalt mix as it allows pavements to take tensile loading. In this study, volumetric and balanced mix designs were conducted to determine the optimum asphalt binder content for three different asphalt mixtures. The type and amount of virgin binder to be used in the RAP mixtures was governed by the RAP binder test results. As the aged RAP binder had lower penetration value than the design virgin binder grade (40/60), a softer 70/100 virgin binder was used to achieve a suitable combined penetration grade of 55 to 60.

The addition of rejuvenators, the method of RAP addition and the temperature and duration of mixing of the recycled asphalt mixture may improve blending between aged and virgin binder (Yin and West 2021). Rejuvenators are added to asphalt mixtures in relatively small quantities to restore the original properties of an aged asphalt binder. The AC20 40% RAP mixture was produced using the additive Iterlow V, and dosage was determined based on the manufacturer's guidelines: 0.13% of the weight of RAP. This dosage was chosen to ensure adequate workability of the high RAP mix.

2.2 Mixture Characterization

To fully characterize the mixtures' performance, both mechanical and functional properties need to be evaluated (Georgiou & Loizos, 2021), this includes stiffness modulus and fatigue resistance, which are two of the key tests undertaken in the current study. Stiffness is a fundamental property of asphalt mixtures obtained by determining the stress–strain response of the material under different loading and environmental conditions. Many studies have been performed to evaluate the impact of RAP on the stiffness of the asphalt mix. A general trend was observed in which the addition of RAP increased the stiffness of asphalt mixtures (Table 1) (Kaseer, et al., 2017). The RAP mixtures will generally have higher stiffnesses than the same mixtures with no RAP. A significant increase in the stiffness of the RAP mixtures could have a detrimental effect on the cracking susceptibility of the mixtures (Mogawer, et al., 2012).

The fatigue resistance of an asphalt mix is its ability to withstand repeated traffic loading without experiencing premature failure. Fatigue cracking as a result of repetitive stress and strain caused by traffic and environmental conditions is considered a primary

Table 1. Stiffness Comparison.

AC 20 - 0% RAP Stiffness @ 20 °C, MPa		AC 20 - 40% RAP Stiffness @ 20 °C, MPa	
Average	7226.8	Average	9393.4
Standard Deviation	411.28	Standard Deviation	943.97
Coefficient of Variation	5.69%	Coefficient of Variation	10.05%

distress mechanism in asphalt pavements (Ghabchi, et al., 2014). Therefore, an effective fatigue performance model is needed that can represent both fatigue damage growth and the fatigue failure criterion in order to define the fatigue life of the pavement (Yin & Pan, 2022). Fatigue cracking starts from the lower layers of the asphalt, where there is higher stress or strain, and moves upward as the frequency of loading increases. Controlling fatigue cracking is one of the most important concerns of experts in this field (Vamegh, et al., 2019). Fatigue cracking is one of the most common distresses in asphalt concrete pavements, it is extremely important to define or predict the fatigue cracking behavior of HMA in flexible pavement design and preservation (Table 2).

Table 2. Fatigue Comparison.

Parameters	Standard	AC 20 - 0% RAP	AC 20 - 40% RAP	Units
Production Temperature	-	160–170		°C
Compaction Temperature	-	150–155		°C
Voids	EN 12697-8	3.5	5.1	%
ε6	EN 12697-24 Appendix E	56	64.0	μs

3 Development of a Sustainable Pavement Design

An ideal performance-based mix design would reflect pavement field performance and enable evaluation of mixtures for a specific climate and use application. This would allow for optimization of material selection and proportions, as well as the introduction of unconventional materials and technologies (Zaumanis, et al., 2018). The empirical nature of current mix design procedures and missing protocols for the characterization of RAP components and an approved mix design do not encourage a greater use of this recycled material (Kaseer, et al., 2017). For these reasons performance-based specifications have the potential not only to improve pavement characteristics and extend service life but they can also help improve production technologies, increase cost effectiveness, and minimize the environmental footprint of asphalt production and paving (Zaumanis, et al., 2018).

One of the objectives is to also compare these designs in terms of their carbon outputs. According to the National Asphalt Pavement Association (NAPA) for 1 ton of HMA the total carbon output is 51.5 kg of CO_2/ton. Whereas for 1 ton of HMA with 40% RAP the total carbon output is 39 kg of CO_2/ton (Fig. 1) (Shacat, et al., 2022). Reducing carbon footprint and energy consumption requires materials and technologies aimed at improving the practices for construction and maintenance, and overall minimize the environmental burdens.

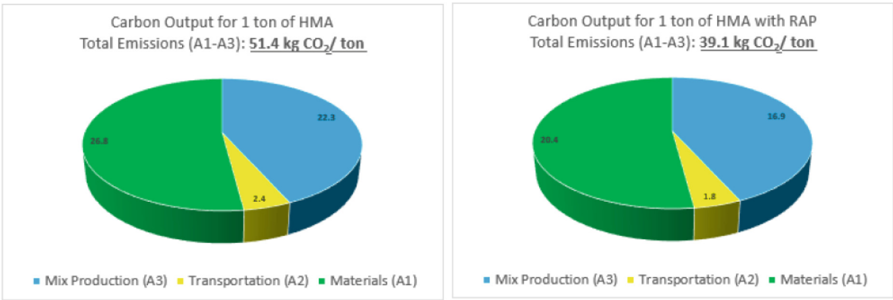

Fig. 1. Potential GHG Emissions reductions.

4 Conclusions

Cost-effectiveness and the environmental impact of asphalt mixtures need to be quantified and compared. Conclusions derived from this study are as follows:

- RAP incorporation increases the stiffness modulus and permanent deformation resistance of asphalt mixtures.
- The RAP mixture performed as well as, or better than, the control HMA mixture with respect to stiffness modulus and fatigue resistance.
- Laboratory fatigue tests aim to evaluate the effect of RAP on durability of asphalt mixes. The RAP mix made with 40% RAP shows the highest number of cycles to failure at each strain level, relative to the control mix. This suggests that the asphalt mix with 40% RAP may have better long-term performance than other mixes made with less or without reclaimed asphalt.
- Both mixtures were designed with similar properties i.e., grading, void, and bitumen content, with RAP content being the most significant variable to affect test results.
- Even though the asphalt mix containing 40% RAP demonstrates a longer fatigue life, possible brittleness issues of the aged binder should be clarified and investigated by testing the rheological behavior of bitumen recovered.
- The use of soft binders and/or rejuvenators can mitigate the stiffening effect of the RAP content, improving the workability of the mix and facilitating the blending between the aged and the virgin binders.

New technologies and practices will need to be developed and implemented to achieve more significant GHG emission reduction goals associated with the cradle-to-gate stages (A1-A3) of asphalt mix production. Several policy changes are needed to accelerate adoption of the technologies and practices needed to achieve these emission reductions. Revision of agency specifications is required to increase the industry's use of RAP and other recycled materials, with balance mix design (BMD) offering a performance-based mix design framework that does not compromise pavement performance (Shacat, et al., 2022).

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Eco-Design of Lightweight Structural Components for Electric Vehicles Made of Advanced Materials

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Abstract. The present paper showcases the results of the ALMA project, whose primary goal is to develop a novel electric vehicle structure for a passenger car, featuring reduced weight and environmental impact. Eco-design principles were incorporated from the early concept stages, integrating approaches like Design for Assembly and Disassembly (DFA/DFD), Design for Recycling (DFR), and functional integration of separate parts into a single structure. A FORD Mondeo with Internal Combustion Engine (ICE) was chosen as a design baseline. Subsequent redesign and material selection iterations led to the development of a novel multi-material Battery Electric Vehicle (BEV) concept, using Advanced High-strength steel (AHSS), low-density grade steel, laminate steel/plastic, and advanced Sheet Moulding Composite (SMC). Crash modeling was performed to virtually validate the design concepts against five different crash scenarios. Ultimately, the ALMA concept car's final design can now boast a mass reduction of 160.5 kg, translating to a 22% weight reduction compared to the baseline BEV.

Keywords: automotive industry · eco-design · electric vehicle · advanced materials · structural components · lightweight · composites · high strength steel · circular economy

1 Introduction

Increasing environmental awareness, as reflected in the recent European Green Deal [1], and concerns related to the growing material demand have motivated the automotive industry to explore new strategies for reducing the environmental impact of both their industrial activities and the entire life cycle of vehicles. In this context, the decisions made in the early stages of design play a crucial role in sustainability. These decisions encompass not only material and manufacturing selections but also extend their effects throughout the entire life cycle of the product, including end-of-life considerations [2].

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 796–801, 2025.
https://doi.org/10.1007/978-3-031-95284-5_111

ALMA is an EU project initiated in 2021 involving 9 partners from 4 different EU countries. The primary objective of ALMA is the development of a novel electric vehicle structure for a passenger car with reduced weight and environmental impact, achieved through the adoption of an integrated circular approach across the entire life cycle, supported by ecodesign principles, Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) tools.

Advanced lightweight materials with structural performances, such as advanced high-strength steel (AHSS) grades, high-performance composites, and hybrid materials, were developed. Beyond lightweighting, other dimensions of the environmental footprint were considered, including efficiency in energy and material consumption, as well as end-of-life options (sorting, recycling, reusing, etc.).

This paper summarizes the eco-design approach followed during the project to select the "right material in the right place" to minimize the environmental footprint while maintaining cost-effectiveness and manufacturability.

2 Methodology

The project commenced with a detailed assessment of the environmental aspects affecting the product from a circular perspective, incorporating cost considerations as a core action to guide subsequent tasks. A Ford Mondeo with Internal Combustion Engine (ICE) was chosen as the starting point. The initial step involved transforming it into a full Battery Electric Vehicle (BEV) version, serving as the baseline for evaluating the achievement of the goal—specifically, a 20% reduction in weight. The project scope encompassed the body-in-white (BIW), chassis, and closures.

The newly transformed BEV baseline design underwent validation through Crash CAE under 5 critical load cases, ultimately reaching a final weight of 727.47 kg. Therefore, to achieve the 20% weight reduction, the weight target for the ALMA ecodesigned structure was set at 581.92 kg or lower.

The baseline was analyzed to identify parts and subsystems subject to modifications, utilizing the innovative materials proposed in ALMA: advanced High-Strength Steel (HSS), low-density grade steel, laminate steel/plastic, and advanced Sheet Moulding Composites (SMCs).

The first criterion was meeting technical requirements in terms of crash behavior. An initial assessment was conducted to identify parts that should remain unmodified, those that could benefit from advanced steels, and those that could potentially be produced using either SMC or other steel grades.

In cases where different materials were eligible, the decision to use the "right material in the right place" was made considering the following metrics:

- Weight saving, expressed as kg saved compared to the baseline part
- Circularity, where a score was assigned based on recyclability potential, ranging from 1 ("currently not recyclable") to 3 ("easily recyclable")
- Number of references saved
- Assembly line compatibility, assigning a score from 1 ("significant changes are required") to 3 ("no changes required")

BEVSIM allows users to measure and compare impacts resulting from design alternatives, lightweight designs, materials, or subsystem choices, recycling technologies, end-of-life scenarios, and future scenarios resulting from changes in electricity grid mixes. This enables easy comparison of complex trade-offs between materials that may be lighter and more sustainable during use but environmentally more costly during production and end-of-life. BEVSIM can also perform various types of impact assessments, including life cycle hotspot analysis, impact assessment, circularity assessment, and economic impacts analysis.

3 Results

In several systems, particularly in those with high mechanical requirements, steel was the only viable solution in terms of crash behaviour. For such parts, different cases were identified:

- Unchanged steel parts: Some of the parts were not modified when there was no alternative material to propose that could fulfil the technical requirements or the lightweighting potential did not justify the change.
- Steel parts with the same geometry as the baseline but lower thickness: The use of more performant steel grades resulted in a reduction of thickness and associated weight saving. There was no need to change the shape, and no possibility to integrate other functions.
- Steel parts with integration of functions: In this case, the use of a more performant steel grade opened new integration possibilities. Systems composed of several parts in the baseline design could be integrated to reduce the references significantly. The systems chosen for integrated redesign were the door panels and the H-Frame structure.

However, some systems could potentially be produced either with SMC or steel, and the choice required a more detailed analysis. Those systems were the dash panel, the rear floor panel, the rear tray, and the battery lid (Fig. 1).

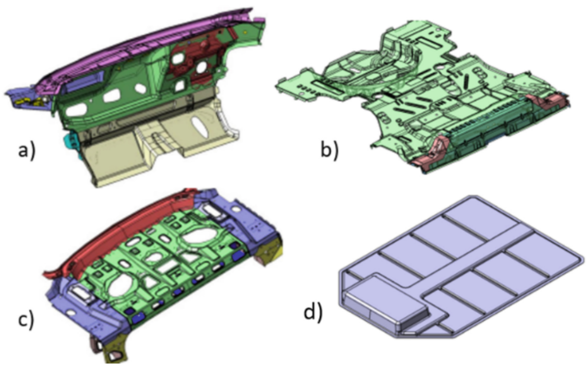

Fig. 1. Images of the considered systems to select SMC vs Steel. a) dash panel b) rear floor panel c) rear tray d) battery lid.. Image produced by the authors using CATIA v4 CAD software.

For these systems, a detailed analysis was made considering the metrics described in Sect. 3. The results are shown in Table 1.

This assessment was complemented by a sustainability analysis using BEVSIM (Fig. 2).

Table 1. Assessment of potential materials for different sub-systems

	Weight saving		Circularity		nº References saved		Assembly line compatibility	
	Kg-saved compared to the baseline		*1 "currently not recyclable" 2 "difficult to recycle/ disassemble" 3 "easily recyclable"*		nº of references saved		1."Significant changes are required" 2."Minor changes are required" 3. "No changes required"	
	Steel	SMC	Steel	SMC	Steel	SMC	Steel	SMC
Dash panel	3,01	5,93	3	1	0	11	3	2
Rear floor panel	17,04	14,09	3	1	0	2	3	2
Rear tray	1,60	3,35	3	1	0	6	3	2
Battery lid	19,84	24,50	3	2	0	0	3	2

The selection of materials for each system was done accordingly:

- The dash panel benefits most from the use of SMC. A drastic reduction in references is possible, with a significant lightweighting potential. The steel option not only maintains the number of references but also has a higher CO2 eq. Intensity, according to BEVSIM analysis. Therefore, this component was selected to be redesigned using SMC materials.
- The rear floor panel in SMC has a lower lightweighting potential than the steel option, which uses a steel laminate. SMC is also more damaging to the environment, according to BEVSIM. It was agreed to select the steel option for this component.
- The rear tray has a lower lightweighting potential for both options. In terms of sustainability, the steel option is less damaging, as shown by the BEVSIM tool. Additionally, no significant changes in the assembly line are needed, while the SMC option would require specific adhesives to withstand an E-coat bath. It was decided to design the component using advanced steel.
- The battery lid has a higher lightweighting potential for both options, and their environmental impact is similar. Since it is assembled after the E-coat process, the SMC allows for the use of debondable adhesives. Therefore, it was agreed to design it using a flame-retardant SMC.

The bill of materials was then completed, and the new total weight of the ALMA structure was reduced to 567 kg. Finally, the new design was validated using CAE