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Sustainable Asset Replacement Considering Environmental Impacts in Railway Sector

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Abstract

This paper outlines the methodological and analytical foundation for RAMS (Reliability, Availability, Maintainability, and Safety) and Lifecycle Cost (LCC) assessment within the NRPCES project, supporting future development of Economic Replacement Time (ERT) considering sustainability KPIs and decision-support tools. The work is aligned with relevant European standards, notably EN 50126 for RAMS and EN 60300 for LCC, and provides a generic, transferable framework applicable across multiple industrial sectors.

The primary objective of this study is to define how probabilistic RAMS indicators and cost drivers can be derived from operational and maintenance data and integrated into a consistent LCC structure. A comprehensive RAMS modelling framework for repairable systems is presented, combining homogeneity testing, trend analysis, and parametric stochastic processes. In addition, CO2 emissions and carbon costs associated with maintenance activities have been identified through maintenance data records and interviews with experts. Thereafter, RAMS outputs are directly linked to LCC drivers, ensuring that failure frequency, repair duration, and downtime are explicitly reflected in economic assessments. The methodology is demonstrated through railway crossing assets installed in the Swedish railway network.

Keywords: RAMS, LCC, railway asset, decarbonization, sustainable replacement strategy, maintenance planning.

1. Introduction

Railways are critical to both freight and passenger transportation and form the backbone of national and international logistics chains and public mobility services. Their importance is expected to increase as climate change mitigation policies promote a modal shift from air and road transport to the rail sector.

Sustainability and climate change challenges have become a global concern, creating an urgent need to mitigate and reduce emission impacts from the entire life cycle of the transport system, including operation and maintenance. Traditionally, maintenance was viewed primarily as a technical engineering activity to restore equipment to its required function. Today, maintenance is increasingly expected to support sustainability goals by minimizing environmental impacts and reducing lifecycle costs. Its contribution to sustainability is reflected in its ability to lower energy consumption, reduce CO2 emissions, reduce the total cost of ownership, and improve safety and quality indicators.

Many studies have aimed to optimize maintenance activities to minimize the total cost of ownership. Jardine and Tsang [1] and Feldman and Valdez-Flores [2] provide different mathematical models for optimizing the replacement of assets considering corrective and preventive maintenance. In these models, the decision variable is the replacement age, and the objective is to minimize the long-run average daily cost. Similarly, Afrinaldi, Tasman, Zhang, and Hasan [3] present a mathematical model for identifying the optimal preventive replacement schedule for a component, considering both economic and environmental impacts.

Studies evaluating the environmental impact of railway maintenance activities are growing in the literature. Ortega, Blainey and Preston [4] present a lifecycle analysis estimating how installing under-sleeper pads (USPs) during track renewal affects carbon emissions on two conventional railway lines in the United Kingdom. Krezo, Mirza, Kaewunruen, and Sussman [5] quantify CO_2 emissions from ballasted-track railway resurfacing using detailed field data from tamping machines, ballast regulators, and ballast stabilisers. They find tamping machines produce the most emissions, followed by ballast regulators and then ballast stabilisers. Kaewunruen, Sresakoolchai and Yu [6] analyse lifecycle cost (LCC) and lifecycle assessment (LCA) for the Xikema No. 1 high-speed railway tunnel in China to consider the environmental impact of rail tunnel construction. Gulcimen, Aydogan and Uzal [7] evaluate the sustainability performance of the Kayseri light rail transit system in Turkey using a full life cycle perspective. It applies an integrated life cycle sustainability assessment (LCSA) that combines environmental LCA and LCC, and social life cycle assessment (S-LCA) to capture environmental, economic, and social impacts together. Landgraf, Zeiner, Knabl and Corman [8] assess the environmental impacts of railway turnouts using a LCA that includes all upstream and downstream processes. It relies on real-life data across the value chain, including service life assumptions and maintenance needs, and converts the impacts into environmental costs using a single-score environmental pricing method.

Vignali [9] compares the environmental impacts of ballasted versus ballastless railway track in Italy using an LCA for 1 km of infrastructure. Contrary to many earlier studies, it finds the ballastless option has a lower overall impact because it lasts

longer (about 90 years) and requires less maintenance. Calle-Cordón [10] introduces an innovative combined RAMS and LCC methodology for railway and road infrastructure that supports condition- and risk-based maintenance planning.
In most of the above-mentioned methods, reliability, availability, maintainability, and safety (RAMS), LCC, and LCA were the core concepts for optimization of replacement interval and maintenance scheduling, which are of vital importance to the railway industry today. The ISO-EN-50126 [11] standard defines the concept of RAMS. Reliability refers to whether a system or equipment can operate stably and perform its intended functions under specific conditions for a certain period of time [12, 13].

LCC (EN 60300) assessment has become increasingly important for railway operators, infrastructure managers, and equipment manufacturers [14]. Traditional methods, which mainly focus on financial costs, are no longer enough to handle the complex challenges of a modern industrial setting. The RAMS & LCC and their integration with environmental KPIs aim to improve infrastructure reliability and, over time, reduce maintenance costs[15, 16].
Prior studies show that maintenance and replacement decisions strongly influence a system's environmental and economic performance, yet research on optimizing when to perform these actions to minimize both impacts remains limited. This paper addresses that gap by developing an integrated LCC model that determines an optimal preventive replacement schedule to minimize an asset's total lifecycle economic and environmental impacts, considering inspection, minimal repair interventions, replacement, and preventive maintenance actions. It does this by (1) auditing and structuring data from existing maintenance systems, then (2) building a probabilistic failure model (3) evaluating cost and CO2 emission release during operation and maintenance phases, to guide maintenance and investment decisions and identify optimal replacement time. This paper disseminates the findings of NRPCES project, which aims to integrate a sustainability dimension into the RAMS framework, supporting CO_2 reduction in transport. This aligns with EU directives and strategic frameworks that mandate significant emissions reductions and promote climate-neutral and resilient industrial and transport systems.

2. Methods

The research methodology consists of the following four steps, including:
Step1: Data collection for the railway asset,
Step2: RAMS modelling framework,
Step3: LCC calculation algorithms
Step4: Integration of LCC with environmental cost(CO_2 cost).
All the above algorithms are dependent to each other, which creates the workflow as illustrated in Figure 1.

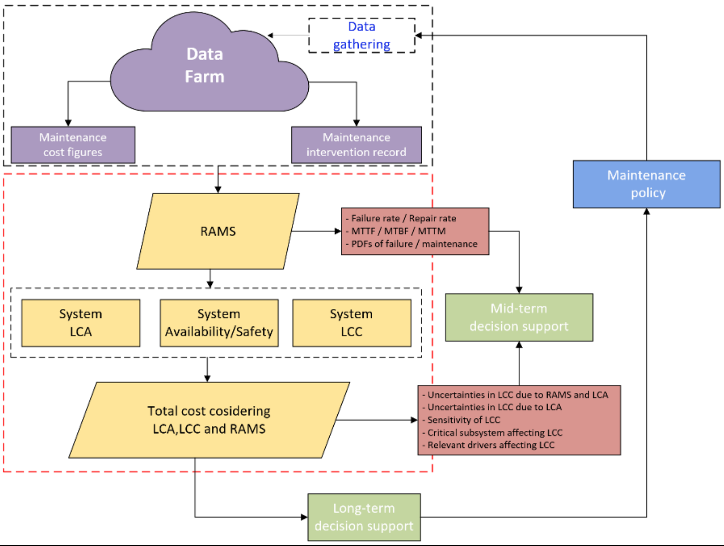

Figure 1: RAMS&LCC algorithms workflow

2.1. Data collection and data preparation

Swedish transport infrastructure databases were used to collect corrective maintenance failures and inspection records for railway crossings. The databases contain detailed information about failures, including installation date, failure date, failure type, repair time, maintenance action type, etc. In addition, maintenance action cost, number of crew, labour cost, spare part, maintenance machinery cost, downtime cost, etc., were collected for LCC assessment.

2.2. RAMS framework

RAMS analysis is one of the core concepts that is implemented in this study. The overall procedure of the RAMS framework is illustrated in Figure 2.

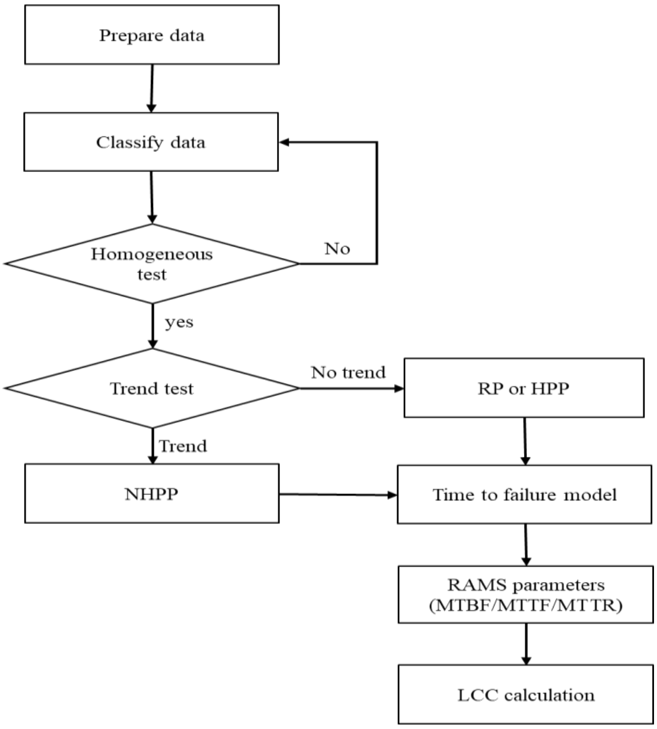

Figure 2: Flowchart of the RAMS modelling framework

The selected asset can be considered as a *repairable system*. To examine appropriate models and processes trend analyses should be followed to identify whether a trend exists in the failure times or not. Several trend tests can be applied: the Military Handbook test, the Laplace test, and the Anderson-Darling test. If the *p*-value is greater than 5%, we conclude that there is no trend in the failure data; otherwise, the presence of a trend is confirmed. The following is a short description of the processes.

- *Renewal processes (RP):* for repairable items, when maintenance actions restore the items to an operating condition that is as-good-as-new (*perfect repair*), and for non-repairable items when their failure data is identical and independently distributed (i.i.d.). In this case, there is no trend between the failures, and an appropriate distribution can be selected.
- *Non-homogeneous Poisson processes (NHPP):* for repairable items when a maintenance action restores the item to an operating state that is as-bad-as-old (*minimal repair*). In this case, there is trend between the failures, which reflect age impact on the failure mechanism.

If a trend is detected in the failure data, a Non-Homogeneous Poisson Process (NHPP) is applied, with the Power Law Process used as the intensity function. If no trend is present, a Renewal Process (RP) is followed. For RP, the best-fitting parametric distribution is selected among exponential and Weibull distributions. Finally, reliability function is defined as the following. For more details of reliability assessment see [13, 17].

Reliability (probability of success) : R(t) = $\int_t^\infty \boldsymbol{f(s)ds}$ [=P(T ≥ t)]

2.3. LCC assessment

LCC for assets comprises all costs incurred over its expected service life, including design, production, installation, operation and maintenance (O&M), and end-of-life disposal. Multiple LCC formulations exist; in this study we adopt the structure used by [14] and [15] expressed in Eq.1:

LCC = Acquisition Costs + Operation and Support Costs + Phase-out Costs

Where:

- **Acquisition Costs** include expenses related to the development stage, such as design, fabrication, production/manufacture, installation, and associated activities.
- **Operation and Support Costs** include costs arising during the operational life of the asset, including operations, maintenance (e.g., inspections, repairs, replacements), support, and failure-related costs.
- **Phase-out Costs** represent the net end-of-life value, including residual/salvage value as well as dismantling and disposal costs.

Within the scope of this work, acquisition and phase-out costs are treated as fixed. Accordingly, the analysis concentrates on operation and support costs**.** These costs may include routine monitoring and inspections, cleaning, lubrication, repair, and other maintenance activities for S&Cs. The frequency and intensity of such activities depend on factors such as the design life of the S&C, track layout, material selection, environmental conditions, operating speed, and traffic volume. This paper specifically examines selected high-frequency corrective maintenance actions. The cost per action is one of the most challenging pieces of information to obtain when developing the LCC model. Here, the data from railway databases and interviews with maintenance entrepreneurs were collected for the assessment. In this study, the cost associated with Co2 emission is embedded in the modeling structure of LCC for corrective maintenance (Eq.1).

$$LCC^{CM} = \sum_{k=1}^{N_y} \sum_{i} \sum_{j} \frac{T_k}{MTBF_{i,j,k}} \left(n_i \cdot MTTR_{i,j} \cdot C^{lab} + C_i^{sp} + C_i^{eq} + C_i^{CO2} \right) \quad \text{Eq.1}$$

Where k denotes the year index $(k = 1, \ldots, N_y = 10)$, i denotes the maintenance action type, and j denotes the component type. T_k is the duration of year $k[h]$.

$MTBF_{i,j,k}$ is the mean time between failures of component j associated with maintenance action i in year $k[h]$. $MTTR_{i,j}$ is the mean time to repair $[h]$. n_i is the number of required workers for maintenance action i. C^{lab} is the labor cost rate $[SEK/h]$. C_i^{sp} is the spare-part cost per intervention $[SEK]$. C_i^{eq} is the equipment cost per intervention $[SEK]$. C_i^{CO2} represents the environmental cost associated with CO_2 emissions generated by maintenance action i, calculated using a carbon price expressed in $[SEK/kgCO_2]$ considering the emission factor per type of fuel.

3. Use Case Applications

3.1. Description of Turnout-Railway crossing asset

Railway S&Cs (or turnout) are an essential part of railway infrastructure, used to guide trains from one track to another (Figure 3) consists of several sub-components, such as rails, check rails, switches, crossings, etc.
In Sweden, railway infrastructure utilizes about 12500 switches and crossings in the network. The maintenance records show that S&Cs are one of the most maintenance-intensive assets in the Swedish railway's infrastructure.

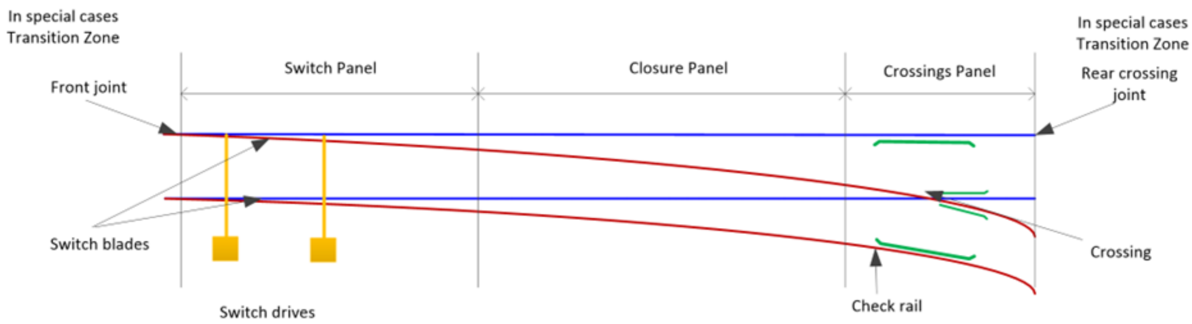

Figure 3. Switches and crossings asset

This work focuses on the crossing part (subsystem of the S&C), since it is the most replaced component in the S&C. A crossing is the node that facilitates the diversion of railway vehicles from one track to another. Crossings are exposed to harsh working conditions due to a dynamic load environment. Consequently, they are prone to defects in the forms of wear, tear, plastic deformation, and cracking, and are subjected to frequent maintenance.
The crossing panel comprises wing rails, guard rails, and the crossing nose. Broadly, crossings are categorized into two types: fixed crossings (Figure 4) and movable (or swing nose) crossings (Figure 5).

Figure 4: Fixed Crossing

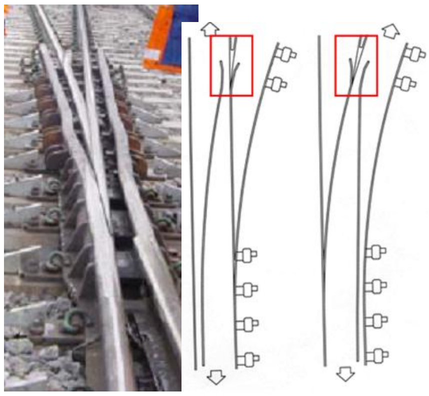

Figure 5: Movable crossing

4. Results

4.1. RAMS for the railway crossing

Based on the RAMS Framework discussed in section 2.2, the parameters of the appropriate model/distribution are estimated for 45 crossing assets. The parameters estimated have been summarized per group in Table 1.

Table 1: Time To Failure Model for railway crossings

Group of Crossing	Number of assets	Distribution model for failure	shape	scale
I	30	NHPP	1.55	20410
II	15	Weibull-2p	0.6	10242.7

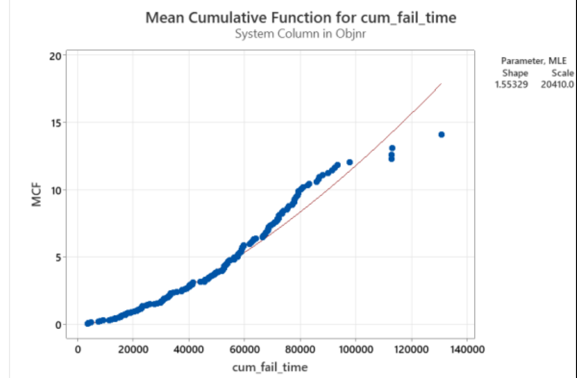

Figure 6: Trend test for group I

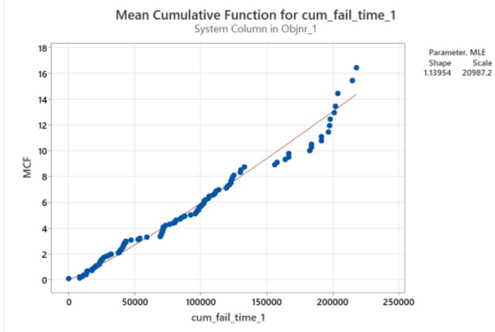

Figure 7: Trend test for group II

Figure 6 (trend test for group I) presents the mean cumulative function (MCF) for the cumulative failure time, where individual points represent observed failures, and the fitted curve corresponds to a power-law NHPP model. Figure 7 can be considered as a trend-free group, and the probability distribution function is an appropriate tool to estimate RAMS parameters. Figure 8 presents probability plots of the time between failures for Group II fitted with the best-fitted Weibull distributions.

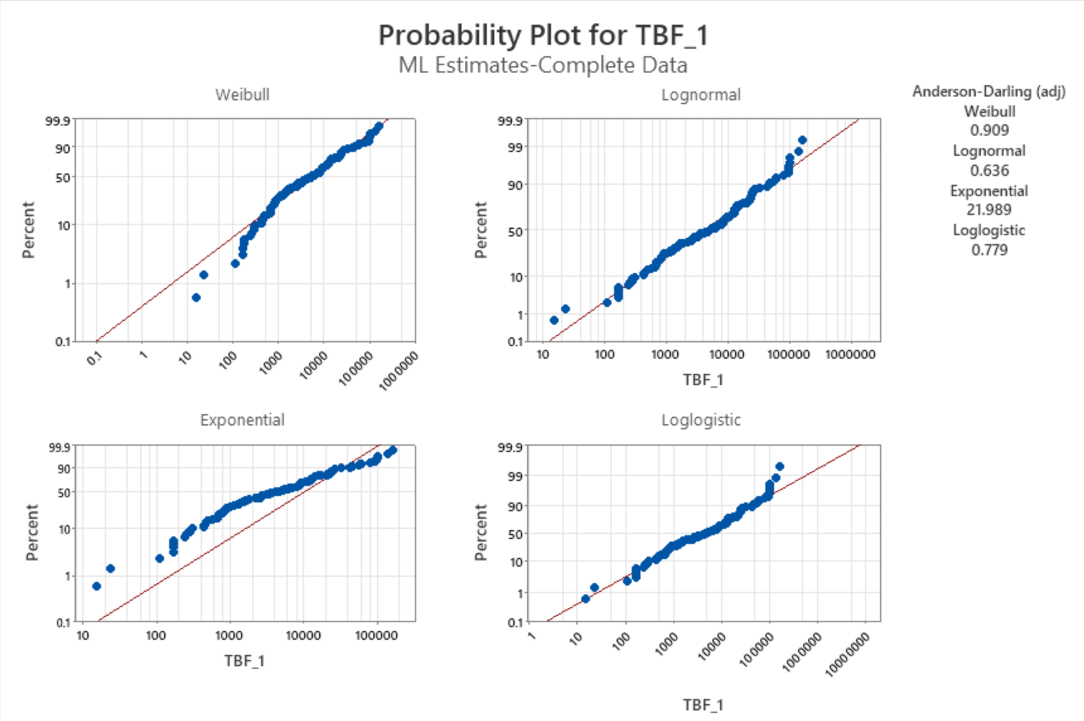

Figure 8: Probability Plot for Time between failures in group II

Table 2 presents the maintainability characterization for two homogeneous railway crossing groups, quantified through the Mean Time To Repair (MTTR) parameter.

Table 2: Mean Time To Repair model for railway crossings

Group of Crossing	Distribution model for repair time	MTTR (h)
I	Weibull	5.11
II	Exponential	5.06

4.2. LCC for the railway crossing

This formulation accounts for both replacement costs and operational costs associated with corrective maintenance activities over the service life of each group.

Table 3: Lifecycle Cost for corrective maintenance for railway crossings

Group	Number of crossings	LCC_{CM}
I	30	26399347.35
II	15	7800545.434

Table 3 presents the estimated lifecycle cost of corrective maintenance for different groups of railway crossings over a 10-year service life. The results reveal substantial variation in corrective maintenance costs across the groups, mainly driven by differences in the number of crossings and their associated failure behavior. Furthermore, Figure 9 illustrates the total CO2 emission of crossing assets per group, and Figure 10 represents the total CO2 emission of crossing per action per group.

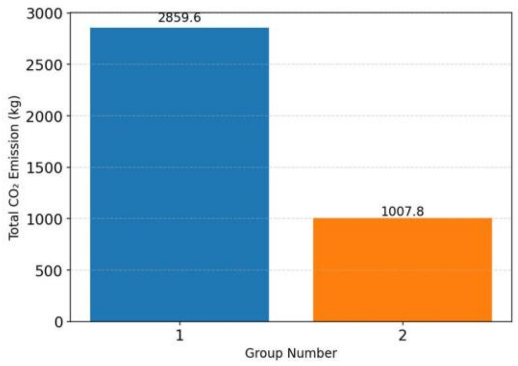

Figure 9: CO2 emitted per group of assets

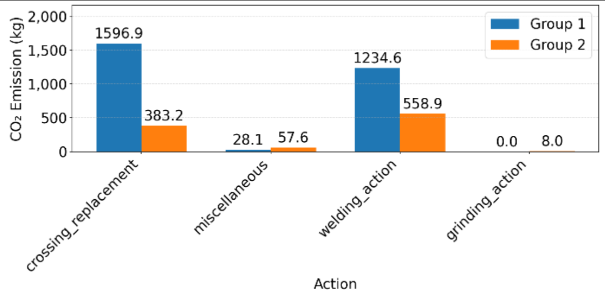

Figure 10: CO2 emitted per group per maintenance action

In addition, the CO2 cost is calculated and presented in Figure 11.

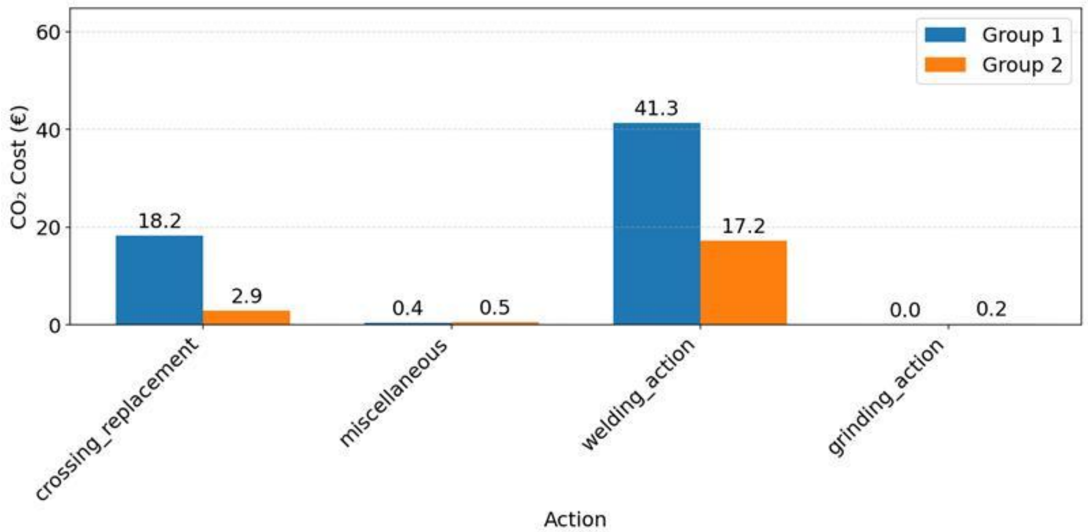

Figure 12: CO2 emissions cost per group per maintenance action

Table 4: Accumulated CO2 emissions and associated cost per group per maintenance action

Group	Replacement Level	CO2_Emission_kg_action	Co2_cost_(sek)_action
I	crossing replacement	1596.86	182
	miscellaneous	28.14	3.5
	welding action	1234.62	413
II	crossing replacement	383.25	28.75
	grinding action	8.04	2
	miscellaneous	57.6	4.9
	welding action	558.91	17.16

The CO2 cost presented in Table 4 shows that for the operation and maintenance phase only, the carbon cost is low; full lifecycle inclusion is expected to change the magnitude and potentially the decision. Since most CO_2 emissions are associated with the manufacturing of crossings and their transport to the railway site, we expect higher costs in the LCC model.

5. Conclusions and Contributions

This study investigates the impact of environmental cost on the optimal replacement time of a railway crossing asset to minimize the economic and environmental impacts. In this study, the cost associated with CO2 emission is embedded in the modeling structure of LCC for corrective maintenance interventions. The estimated carbon cost associated with corrective maintenance activities is low for the studied assets and is therefore unlikely to affect the optimal replacement decision when only the operation and maintenance phase is considered**.** However, manufacturing and transport are expected to dominate lifecycle emissions for crossings; including these phases is likely to increase the environmental cost component and may influence the replacement timing.

By reducing environmental impacts and optimizing lifecycle costs through replacement policies that explicitly consider environmental footprints, the proposed framework aims to enhance resource efficiency and support decarbonization during the operation and maintenance of long-life railway assets and production facilities.

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