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# Integrating Life Cycle Assessment Based Key Performance Indicators for Sustainable Railway Asset Management

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## Abstract

Sustainable decision support system for asset management essentially requires an integrated approach that considers operational performance, maintenance strategies, environmental sustainability, and economic efficiency. This study presents a systematic methodology for identifying and selecting Key Performance Indicators (KPIs) for translating complex environmental data into quantitative insights for railway and manufacturing assets. The proposed framework integrates life-cycle assessment (LCA) based indicators across upstream, core, and downstream life-cycle stages to quantify environmental impacts across the full asset life cycle. The Global Warming Potential (GWP) considered as the primary indicator, reflecting the essential role of carbon emissions in sustainability objectives, while energy consumption, waste management, and service water are defined as secondary KPIs. Tertiary KPIs include resource use and recycled content, providing additional support to circularity and reduced carbon emissions goals. This framework provides a consolidated foundation for comparing and optimizing maintenance (corrective and predictive) and replacement strategies. Overall, this work contributes to support effective environmental monitoring to determine Optimal Replacement Time (ORT) for railway assets.

**Keywords:** life cycle assessment, global warming potential, railway infrastructure, environmental KPIs, RAMS, life-cycle cost

# 1 Introduction

Railway sector is an asset intensive sector. Conventionally, such sectors primarily focus on reliability, availability, maintainability and safety (RAMS), while maintaining cost-effective performance. However, it often overlooks environmental sustainability that they drive from energy consumption, material use and greenhouse gas emissions throughout their life cycle from raw material extraction, manufacturing to operation, maintenance, and end-of-life phases. With growing regulatory requirements, climate targets, and sustainability commitments for sustainability, integrating environmental considerations into asset management has become imperative into asset management decision support systems.

Environmental sustainability in Asset Management requires explicit consideration of environmental criteria into asset management frameworks, particularly for high maintenance infrastructure assets such as railway crossing assets. Sustainable asset management extends traditional framework by incorporating long-term environmental considerations into asset value decisions measures. LCA has been extensively applied to railway infrastructure to identify environmental hotspots associated with construction, maintenance, and renewal activities [1–4]. It is scientifically robust to evaluate environmental impacts across all phases of an asset's life cycle (Figure). ISO 14050 and ISO 14044 states about the Life cycle analyses (LCAs) analysis (Figure 1) [5]. The UIC Sustainability Indicators for Railways project developed six KPIs to monitor the rail sector's environmental impact: energy consumption; renewable energy usage; greenhouse gas emissions; local air pollution; noise emissions; and land use [6,7].

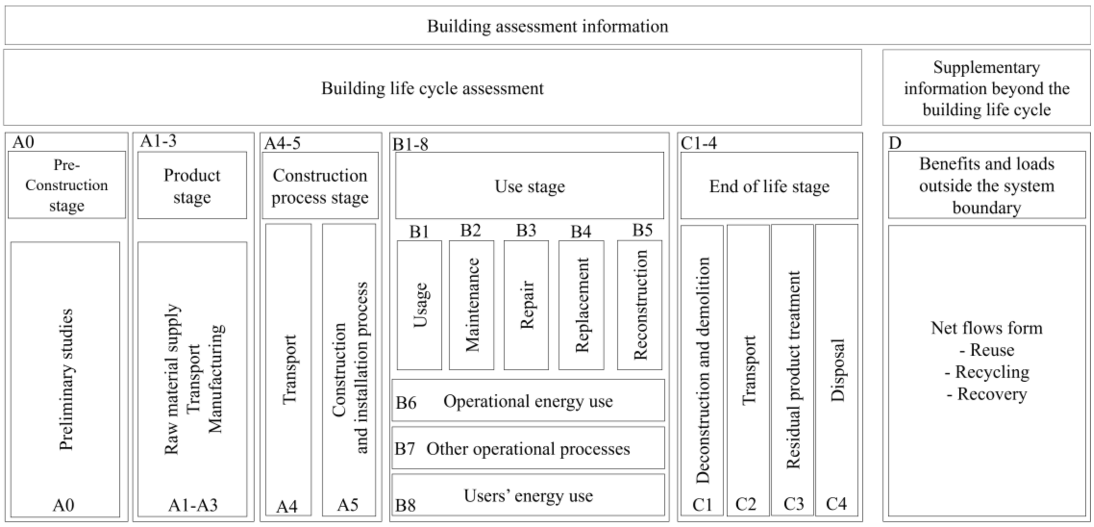


*Figure 1: Asset's life cycle stages*

Stage A represents the pre-construction, product, and construction process phases and follows a cradle-to-gate approach, capturing all environmental impacts from raw material extraction through manufacturing, transportation, and installation. Stage B covers the use phase, often described as cradle-to-practical completion, and evaluates the environmental impacts that occur during the operational life of the asset, including energy use, maintenance, repair, and replacement. Stage C represents the end-of-life stage, or cradle-to-grave, assessing impacts related to deconstruction, transport, waste processing, and final disposal. Finally, Stage D lies beyond the end-of-life boundary and considers the long-term environmental benefits associated with material recovery, reuse, recycling, and substitution in accordance with a cradle-to-cradle perspective. Several literatures emphasize the importance of incorporating environmental criteria into asset management frameworks. For instance, Sherif et al. [8] and Kibira & Feng [9] proposed systematic multi-criteria decision approaches to identify and prioritize environmental KPIs. Glišić et al. [10] proposed a bottom-up, LCA-driven methodology to derive unit-process-level environmental KPIs. Cooper et al. [11] used participatory research workshops to develop and weight KPIs. Table 1 provide the summary of LCA lifecycle phases addressed in different sectors [12–20].

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*Table 1: Life Cycle Assessment (LCA) in different sectors for sustainable asset management*

| Study | Asset Type | Sector | Geographic Context |
|---|---|---|---|
| Janjua et al., [12] | Residential buildings | Construction | Western Australia |
| Nathman et al., [13] | Pavements | Transportation | Not specified |
| de-Almeida-e-Pais et al., [14] | Buildings, infrastructure, equipment | Energy-intensive sectors | Broad applicability |
| Larsen et al., [15] | Buildings | Construction and real estate | Europe |
| Carrión et al., [16] | Pavements | Transportation | Europe |
| Jones et al., [17] | Government office buildings | Construction | Australia |
| Guan et al., [18] | Not specified | Various sectors | Not specified |
| Cooper et al., [11] | Housing stock | Social housing | UK (London) |
| Gunarathna et al., [19] | Road transport assets | Road transportation | Australia |
| Stipanovic et al.,[20] | Highway bridges, airport runways | Transportation infrastructure | Europe (Spain, Croatia) |

Despite growing attention, existing approaches often lack harmonization in indicator selection, system boundaries, and functional units, limiting comparability and practical deployment across asset classes. This paper aims to provide a sustainable asset management framework through integrating LCA based KPIs into existing management systems. In general, LCA data is often siloed and not systematically translated into actionable management metrics. Consequently, this study bridges the gap by proposing a structured framework for integrating LCA-based KPIs into an asset management framework. This framework supports the transition toward green and sustainable asset management by optimizing the ORT of railway assets while explicitly incorporating sustainability factors into the decision-making process.

## 2 Methodology

The methodological approaches for integrating LCA into asset management varied in complexity and comprehensiveness. It emphasizes (i) selecting Key Performance Indicators (KPIs) for environmental impact monitoring and (ii) structuring these indicators across upstream, core, and downstream LCA stages. Key Performance Indicators (KPIs) provide a practical mechanism to operationalize LCA results by translating environmental impacts into measurable, comparable, and decision relevant metrics. The specific KPI derived from LCA varied significantly across asset types, however directing toward a mutual objective i.e. sustainability. This KPI selection framework provided a route map for improving sustainability while addressing carbon emission targets.

## 3 KPI Selection and Integration Framework

The identification of well-structured Key Performance Indicators (KPIs) is essential for translating complex environmental data into actionable insights. These indicators enable the quantification of an asset's environmental footprint and allow for performance comparisons across different life cycle stages.

Following KPIs were designed to be measurable, directly affected by maintenance work across heterogeneous assets (Table 2).

*Table 2:Harmonised definition for selected KPIs*

| Tier | KPI | Definition | Unit |
|---|---|---|---|
| Primary | Global Warming Potential (GWP) | Climate change impact of the activity or asset life cycle, based on CO2-equivalent emissions. | kg CO2eq/FU |
| Secondary | Energy consumption | Total electricity and fuel energy required in the defined life-cycle stages. | kWh/FU or MJ/FU |
| Secondary | Waste generation | Mass of solid waste generated, including replaced components and consumables, by treatment route where possible. | kg/FU or % recycled |
| Secondary | Service water consumption | Volume of service/process water consumed in manufacturing or maintenance activities. | L/FU or m3/FU |
| Tertiary | Recycled content (resource use) | Share of recycled or reused material in components or consumables used for replacement or renewal. | % recycled content |

The framework adopts KPIs integration across the system boundaries (i.e. upstream, core, and downstream stages of the LCA), ensuring comprehensive environmental impact coverage. The system is defined based on the activities it includes. It should be noted that each use case defines its functional unit based on EN 15804, which refers to functions or performance characteristics of the product.

# 4 Optimal Replacement Time (ORT) Modeling

The Optimal Replacement Time (ORT) identifies component failure replacement based on technical, economic, and environmental factors simultaneously (Figure 2). In this work, integration frameworks for sustainable asset management are addressed through balancing technical reliability (e.g. RAMS, maintenance action etc.), lifecycle cost (LCC), and environmental performance (LCA). Effective integration requires asset-specific KPI selection, which includes distinct asset characteristics.

- **Cost Function:** Minimizes total expected cost per unit time, incorporating inspection, maintenance and failure replacement costs. This was addressed through cost-focused indicators including maintenance costs, running costs, and lifecycle investment calculations

- **Environmental Impact Function:** Minimizes total expected environmental impact per unit time, using GWP as the primary metric.

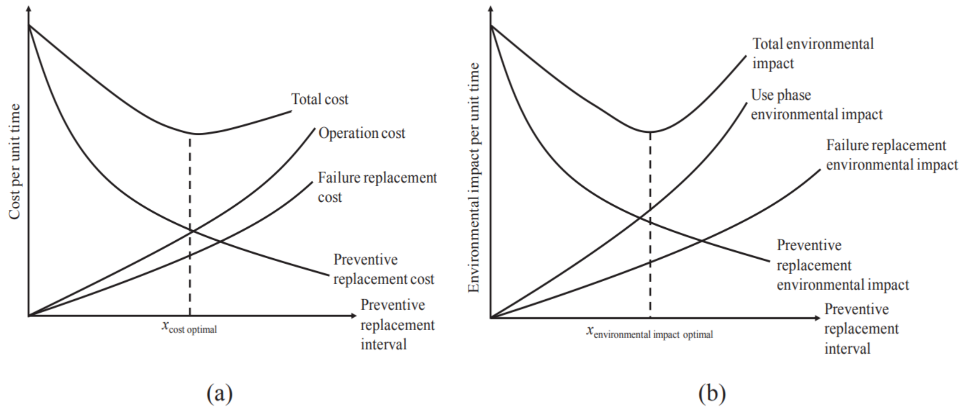


*Figure 2: Optimal preventive replacement interval, (a) cost minimization, (b) environmental impact minimization [21]*

# 5 Turnout crossing Use Case Applications

For turnout crossing LCA stages A1 to A5 are classified as upstream processes, stages B1-B6 are classified as core processes, and stages C1–C4 are classified as downstream processes (Table 4). The functional unit for this use case is defined as CO2 emission per asset per unit activity.

*Table 3: Stage coverage and KPIs for turnout crossing*

| Life-cycle stage group | Representative processes | Main KPIs |
|---|---|---|
| Upstream (A1-A5) | Raw materials, manufacturing, transport to site, installation. | GWP (embodied) |
| Maintenance (B2) | Inspection, grinding, lubrication, cleaning, snow management, transport to/from site. | GWP; energy; service water (cleaning); waste (consumables). |
| Repair (B3) | Preheating, welding repair, grinding, logistics. | GWP; energy; waste. |
| Replacement (B4) and end-of-life (C1-C4) | Component renewal and disposal/recycling of removed parts. | GWP; waste; recycled content (procurement). |

The optimization of new replacement of railway assets considering sustainability KPIs requires detailed operation and maintenance of crossing assets across its life cycle. The data needs to be collected for the ORT optimisation are Mean time between failure, mean to repair, Repair frequency, Repair cost, Logistic cost (per maintenance activity), No. of maintenance crew (labour), Cost of maintenance crew per hour or per day or per action, Cost of spare part, and mean logistic time. In addition to abovementioned parameters for LCC and RAMS assessment, environmental factors also need to be calculated. The ORT for turnout crossing integrates LCC, RAMS and LCA assessment. For the RAMS assessment various types of data including failure time and repair time are evaluated from the available databases (Maintenance records and EPDs). Afterwards the ORT model integrates LCC analysis with carbon cost assessment. The LCC is evaluated using RAMS parameters. Thereafter for LCA (in terms of cost) carbon price per year is quantified. Finally, the integration of the assessment provides ORT for railway crossing asset. The detailed methodology is provided in the figure below (Figure 3).

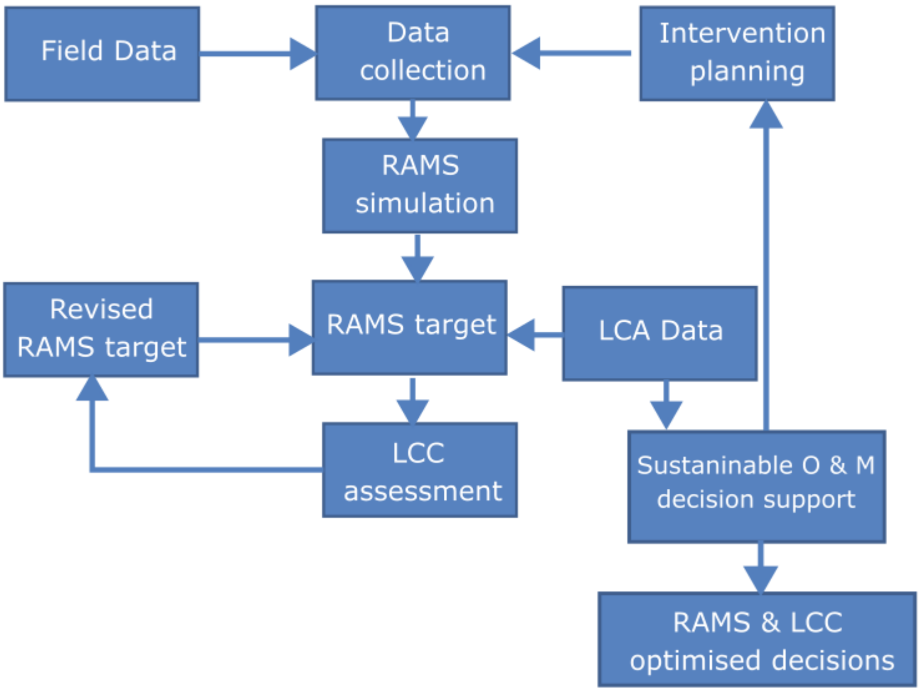


*Figure 3: Flowchart illustrates LCA integration with RAMS and LCC assessments*

The model updates quarterly as new failure, censoring, and inspection records accumulate, refining degradation parameters and maintenance effect estimates.

## 6 Conclusions and Future work

This study proposes an LCA based integrated framework for sustainable asset management and optimal replacement time of railway infrastructure. LCA-based KPIs (primary (GWP), secondary KPIs (energy, waste, water), and tertiary KPIs (resource use) are consistently applied across to upstream, core, and downstream LCA stages and tailored with turnout crossing specific functional units. The framework demonstrates how environmental performance can be monitored and integrated into ORT models that also account for technical reliability (e.g. RAMS, maintenance action etc.), and LCC, thereby aligning sustainability objectives and supports the transition to circular.

Future research directions include expanding KPI coverage to social dimensions, refining multi-criteria ORT formulations that explicitly weight cost versus environmental impacts and developing digital tools that automate KPI calculation from operational data streams.

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