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“Asset MAnagement in the new Dlgital Twins environment” (AMADIT)

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1. EXECUTIVE SUMMARY

This document constitutes **Deliverable A2.D4.2**, whose objective is to define the procedure for incorporating carbon and water footprints, environmental costs, and circularity indicators into Asset Investment Planning (AIP) tools and Applications (Apps).

The document develops: (i) methodologies for calculating carbon footprint (CF) and water footprint (WF) (ISO 14067 [1] ISO 14064-1 [2], ISO 14064-2 [3], ISO 14064-3 [4], GHG Protocol [5], ISO 14046 [6]); (ii) procedures for internalising environmental costs (including Green-LCC) [7]; (iii) circularity indicators adapted to maintenance; and (iv) their digital integration into AIP modules (IoT, digital twins, AHI) [8].

Key results include the formalisation of the Green-LCC approach for CAPEX and OPEX decision-making under environmental criteria [7] [9], as well as the integration of the ecological footprint into digital twins to monitor and simulate different scenarios [10] [11]. In addition, a six-step methodological procedure for calculation has been developed, designed to be replicable in different sectors such as rail transport, energy, and infrastructure. The expected impact of this proposal focuses on reducing the environmental impacts associated with maintenance operations, optimising costs through the integration of circularity principles, and contributing to the goal of climate neutrality by 2050.

2. INTRODUCTION

Industrial and infrastructure asset management today faces a double challenge: ensuring environmental sustainability and harnessing the potential of digitalisation. The convergence of the ecological transition and the digital transition opens the door to new ways of designing, operating, and maintaining assets, integrating environmental criteria into the core of decision-making [7].

In this context, the AMADIT project, led by group A2, has identified the need to establish a robust and replicable procedure for integrating carbon footprint, water footprint, environmental costs, and circularity indicators into the AIP tools and apps of digital twins designed for asset management and maintenance. Throughout the document, references are made to the already published contributions of Group A.2 on this environmental issue and AIP models.

AIP models are conceived as a digital ecosystem to support intelligent asset management, comprising monitoring, analysis, prediction, and prescription modules, supported by IoT, big data, and artificial intelligence, to be integrated into digital twins [8]. Until now, these tools have been included in platforms whose primary focus is operational and economic optimisation. However, to meet European decarbonization and circular economy objectives, it is essential to add a layer of environmental sustainability to the platform that is natively incorporated into its digital functionalities.

This deliverable contributes to that objective by defining a comprehensive procedure that:

- Adapts environmental footprint methodologies (carbon and water) to the field of asset management.
- Integrates environmental costs into life cycle models, proposing Green-LCC as an extension of traditional LCC [9] [7].

- Defines circularity indicators adapted to maintenance and asset management operations.
- Establishes digital integration mechanisms for AIP tools, ensuring interoperability with other modules (AHI, prescriptive analytics, Systemic Impact Factor (SIF), etc.) [12] [13].

This deliverable covers maintenance and asset management operations in the case studies, including the development of a model for calculating carbon footprint and water footprint. The design of the mathematical model facilitates the subsequent development of the projection to 2030 and the determination of the necessary reductions by 2050. It includes environmental costs (such as the Social Cost of Carbon (SCC) and water) and circularity (including reuse, recycling, and durability). The study of reductions up to 2050 presents many issues related to the lifespan of assets, the design of new equipment, and its entry into service.

The document responds to task A2.T4.2, which requires calculating footprints, environmental costs, and circularity indicators, and integrating them into AIP models and tools with a 2030–2050 vision. Milestone 2 (Design) is fulfilled by providing the detailed procedure, digital integration architecture, and KPIs for validation.

The deliverable has the following structure:

- Section 3. General methodology of the procedure.
- Section 4. Calculation of carbon and water footprints.
- Section 5. Associated environmental costs.
- Section 6. Circularity indicators.
- Section 7. Integration into AIP tools and apps.
- Section 8. Proposed procedure (summary).
- Section 9. Implementation of environmental tools in the cloud using digital twins.
- Section 10. Validation and expected results.
- Section 11. Conclusions and recommendations.
- Section 12. Bibliographical references.

This deliverable, in addition to meeting the design milestone, provides a practical methodological framework for organisations to incorporate sustainability criteria into their asset management, moving towards Asset Management 5.0 models, where operational excellence, sustainability and digitalisation converge.

3. GENERAL METHODOLOGY OF THE PROCEDURE

3.1. Reference principles

The proposed procedure is based on a set of methodological and regulatory principles that ensure its consistency with international best practices:

- Asset management (ISO 55000) [14]: establishes the need to integrate environmental, economic and social criteria into decision-making on assets throughout their life cycle.
- Environmental management (ISO 14000 family of standards): in particular, ISO 14064 for calculating greenhouse gas emissions and ISO 14046 for water footprint.
- Circular economy (EU Action Plan [15], Ellen MacArthur Foundation [16]): reference framework for the selection of circularity indicators.

- Digitalisation and digital twins: as enabling technologies for capturing, processing and representing environmental information on assets [8] [17].
- Life cycle cost (LCC) models: expanded to include environmental costs, giving rise to Green-LCC (G-LCC) [7].

These principles are articulated within the concept of AIP tools and models, understood as a digital ecosystem that supports asset management through real-time data, advanced analytics and decision support [9].

3.2. Methodological process

The procedure consists of six sequential but interconnected stages:

1. Identification of relevant maintenance and asset management operations that generate environmental impacts.
2. Definition of system boundaries and data collection (energy, materials, water, waste, emissions).
3. Calculation of carbon and water footprints using standardised methodologies.
4. Assessment of environmental costs through economic internalisation of emissions and consumption.
5. Selection and calculation of circularity indicators, adapted to the assets and operations under analysis.
6. Integration into the AIP model ecosystem, ensuring interoperability, visualisation and use in decision-making.

The modular nature of the methodology allows each stage to be deployed progressively, depending on the organisation's degree of digital and environmental maturity [7] [8].

4. CALCULATION OF CARBON AND WATER FOOTPRINT

4.1. Definitions used in the development and scope of emissions

- Carbon footprint: measurement of all greenhouse gases (GHG) emitted directly or indirectly by an activity, expressed in tonnes of CO₂ equivalent (tCO₂e).
- Water footprint: total volume of water consumed, degraded or polluted throughout the life cycle of a product, service or process [7].

The procedure considers the three scopes defined by the GHG Protocol:

- Scope 1: direct emissions (fuels, internal processes).
- Scope 2: indirect emissions from electricity consumption.
- Scope 3: indirect emissions associated with the value chain (materials, transport, waste).

In the case of the water footprint, the following categories are distinguished:

- Blue water (direct consumption from surface or underground sources).
- Green water (use of rainwater stored in the soil).
- Grey water (volume needed to assimilate pollutants).

4.2. Methodologies and standards

The procedure is based on recognised methodologies:

- ISO 14064-1:2018: specifies principles and requirements for quantifying and reporting GHG emissions.
- ISO 14064-2:2019: specifies project-level guidance for quantifying, monitoring and reporting greenhouse gas emission reductions or removal enhancements.
- ISO 14064-3:2019: establishes guidance specifications for the verification and validation of greenhouse gas statements.
- ISO 14067-1:2018: establishes requirements and guidelines for quantifying greenhouse gases and the carbon footprint of products.
- GHG Protocol (Corporate Standard): widely used in organisations and projects.
- ISO 14046:2014: specifies principles, requirements and guidelines for water footprint assessment.
- Life Cycle Assessment (ISO 14040 (ISO 14040 [18], ISO 14044 [19]): these two standards define the phases of life cycle analysis, namely: objectives and scope, inventory analysis, impact assessment and interpretation of results.

In addition, digital modelling and open software tools (e.g. openLCA) are integrated, allowing life cycle data to be combined with environmental footprint data [9].

4.3. Calculation procedure

The procedure consists of the following steps:

1. Data inventory (Life Cycle Inventory, LCI):
 - Energy consumption (electricity, fuels).
 - Water consumption (m³).
 - Material consumption (kg).
 - Emissions and discharges.
 - Waste generated.
2. Allocation of emission/consumption factors:
 - GHG emission factors according to the Intergovernmental Panel on Climate Change (IPCC) and national databases.
 - Reference water footprint factors (e.g. Water Footprint Network).
3. Calculation of results:
 - Total emissions in tCO₂e = Σ (activity data × emission factor).
 - Total water consumption = Σ (activity data × water factor).
4. Standardisation and verification:
 - Comparison with sectoral reference values.
 - Validation through data auditing or digital traceability (blockchain, digital twin records) [17].
5. Integration with digital models:
 - The calculations are incorporated into the digital twin of the asset, linked to its Asset Health Index (AHI), so that the technical health status is complemented by the environmental status [8].

4.4. Future projection (2030–2050)

The procedure includes the subsequent development of a prospective module that allows for the simulation of decarbonisation and water management scenarios towards the milestones set by the EU for 2050:

- 2030: 55% reduction in emissions compared to 1990 (European Green Deal).
- 2050: climate neutrality.

To this end, prediction models are applied based on:

- Energy efficiency and sectoral decarbonisation trends.
- Water transition scenarios in critical regions.
- AI-based prediction algorithms (machine learning) that enable consumption and emissions trends to be estimated [11] [20].

In this way, asset managers will be able to visualise environmental footprint trajectories and plan investments and maintenance actions consistent with neutrality objectives.

5. ASSOCIATED ENVIRONMENTAL COSTS

5.1. Concept and types of environmental costs

Environmental costs represent the economic value associated with the environmental impacts generated during the operation, maintenance and management of assets. Traditionally, they have not been included in business accounting; however, their incorporation is essential to realistically reflect the total cost of ownership (TCO) of an asset [7].

There are three types of costs. Direct costs arising from emissions, discharges, waste, water consumption or materials (e.g. discharge fees, purchase of emission rights). Indirect costs associated with regulatory and reputational risks, technological obsolescence or loss of competitiveness, and avoided costs, due to savings from the implementation of energy efficiency measures, waste reduction or the circular economy.

5.2. Quantification models

The procedure provides for the incorporation of different approaches to the internalisation of environmental costs:

1. Social cost of carbon (SCC): monetisation of the social damage caused by each tonne of CO₂ emitted. Various international agencies estimate this to be between €50 and €100/tCO₂e, with an upward trend expected to continue until 2050.
2. Economic value of water: allocation of costs to water consumption considering local scarcity, water stress and resource quality. This may include both supply costs and externalities due to pollution.
3. Shadow pricing: allocation of internal prices to environmental impacts, even if they are not taxed, to guide corporate decisions.
4. Marginal abatement cost: assessment of the investment required to avoid or reduce an additional unit of environmental impact.

The Green-LCC (G-LCC) formula integrates these costs into the life cycle analysis [7].

$$G - LCC = LCC + C_{CO2} + C_{H2O} + C_{others}$$

Donde:

- LCC = Total life cycle cost (financial).
- C_{CO2} = Cost associated with GHG emissions.
- C_{H2O} = Cost associated with water consumption and pollution.
- C_{others} = Other environmental costs (waste, acidification, smog, etc.).

Furthermore, the proposed cost calculation methodology is based on an adaptation of the Woodward model [21], widely used in life cycle cost analysis studies. This model allows the total costs of the asset to be broken down into components representing its acquisition, operation, maintenance, failures and residual value, providing a systematic structure for the economic calculation of the life cycle. In the context of this project, the model has been extended to include environmental and health parameters of the asset (AHI), so that economic decisions can incorporate both environmental impacts and the technical condition of the system.

The calculation of life cycle costs in present value is expressed according to the general equation:

$$LCC = IIC + OC + PMC + TCPF + MMC - RV$$

where IC represents the initial investment cost, OC the operating costs, PMC the preventive maintenance costs, TCPF the total cost per failure, MMC the major maintenance costs and RV the residual value.

In the recent proposal by the AMADIT group [22], this model is extended to include an extended life cycle formulation (LCC-Extended), which considers actual, estimated and prospective costs throughout the entire useful life of the asset and its possible extension:

$$LCC_{\text{Extended}} = C_{\text{Actual}} + C_{\text{Estimated}} + C_{\text{Prospective}}$$

In this way, the methodology allows for the incorporation of scenarios involving service life extension, future investments and decommissioning costs, while also integrating the effects of technical degradation and changes in the condition of the asset through the Asset Health Index (AHI).

5.3. Integration into decision models

The inclusion of environmental costs allows:

- Expanding traditional CAPEX/OPEX towards a sustainable total cost approach.
- Evaluating maintenance alternatives not only for their financial cost, but also for their integrated environmental impact [9].
- Promote servitisation and circularity strategies, in which the reduction of impacts also measures value.

In this way, AIP tools can generate outputs, represented in comparative dashboards that show the performance of different strategies (e.g. replacement vs. reconditioning of a component) in both economic and environmental terms [13].

Within this framework, the Green-LCC developed in the AMADIT project is conceived as an evolution of Woodward's classic model [21], in which environmental costs (carbon footprint, water footprint and circularity) are integrated into traditional economic categories (CAPEX and OPEX). In this way, Green-LCC provides a broader view that combines economic and environmental sustainability, allowing not only the financial cost of the asset to be quantified, but also the impact associated with its environmental performance.

To enhance the accuracy of the calculation, a Failure Frequency Correction Factor (FCF) derived from the Asset Health Index (AHI) has been incorporated, which adjusts failure rates and maintenance costs based on the asset's health status. This factor, introduced in the research presented at ESREL 2025 [22], is calculated as:

$$FC = [1 + (C \cdot H) + (C \cdot H)^2/2! + (C \cdot H)^3/3!]$$

Where C represents a constant that defines the probability of failure in the most unfavourable condition, and H is the value of the health index (AHI). When the AHI exceeds the threshold of 4, a proportional correction is applied, increasing the costs associated with maintenance and repair activities. This dynamic correction improves the representativeness of the LCC model, directly linking the technical condition of the asset with its total cost and environmental impact.

6. CIRCULARITY INDICATORS

6.1. Conceptualisation

The circular economy promotes keeping materials and products in use for as long as possible, minimising waste and reducing pressure on natural resources. In the context of industrial assets, circularity relates to durability, reuse, recyclability and efficiency in the use of materials [7].

6.2. Selection of applicable indicators

here are multiple reference frameworks for measuring circularity, including the Ellen MacArthur Foundation indicators, the Material Circularity Indicator (MCI), and the EU Circular Economy Monitoring Framework indicators.

In the case of asset management and maintenance, the procedure proposes indicators adapted to specific operations:

1. % of recycled or reused materials in maintenance operations.
2. Average lifespan of components compared to their design lifespan.
3. Refurbishment rate compared to replacement (ratio of repaired + reused components vs. replaced by new ones).
4. Resource efficiency = functional output of the asset/material and energy input.
5. Waste recovery rate (recovered material over total waste).
6. Asset circularity index (ACI): a composite metric that integrates useful life, reuse and recycling.

A more specific study was conducted on rail transport, considering the possibility of using specific indicators:

Locomotives (diesel, electric or hybrid) have significant impacts on energy, emissions and maintenance. Recommended indicators:

- Carbon footprint (kg CO₂-eq), due to fuel or electricity consumption during operation.
- Primary energy consumption (MJ or kWh), including energy for manufacturing, operation and maintenance.
- Global warming potential (GWP), to compare technologies (diesel vs electric).
- NO_x and particulate emissions (kg), especially relevant in diesel locomotives.
- Water footprint (m³), for manufacturing and cleaning processes.
- Recyclability rate (%) of components such as batteries, engines, and chassis.

In passenger or freight wagons, although they have a lower operational impact, they are relevant in terms of materials and maintenance. The following indicators can be used:

- Material consumption (kg), steel, aluminium, plastics, etc.
- Carbon footprint (kg CO₂-eq), in manufacturing and maintenance.
- Acidification potential (kg SO₂-eq), from industrial processes in manufacturing.
- Eutrophication potential (kg PO₄³⁻-eq), from discharges or chemical processes.
- Recyclability rate (%) of structures, coatings, and electrical systems.

In auxiliary systems (air conditioning, signalling, electrical control) installed on locomotives and carriages, the impact is more diffuse but significant in terms of energy efficiency and electronic waste. The following indicators could be considered:

- Energy consumption (kWh), in continuous operation.
- Carbon footprint (kg CO₂-eq), from electronic components and refrigerants.
- Human toxicity/ecotoxicity potential, from the use of heavy metals and hazardous substances.
- Energy recovery rate (%), from electronic waste at the end of its useful life.

6.3. Calculation and integration procedure

The procedure for incorporating circularity indicators into AIP models includes the following:

1. An inventory of materials and components for each asset (structured in its digital twin).
2. A digital record of maintenance operations, identifying whether they involve replacement, reconditioning or recycling [17].
3. Automatic calculation of ratios using algorithms in AIP tools.
4. Display on dashboards, together with environmental footprint and cost indicators.

6.4. Examples of application

- In railway maintenance, the reconditioning vs. replacement ratio allows us to measure the extent to which bogies, wheels and auxiliary systems are being utilised [17] [20].
- In energy converters, the average life of capacitors or Insulated Gate Bipolar Transistors (IGBTs) compared to their design life reflects the effectiveness of preventive maintenance strategies [9].
- In electrical substations, the recovery rate of waste from transformers or switches helps to assess the circularity of the system [13].

7. INTEGRATION INTO AIP AND APPS TOOLS

7.1. Reference digital architecture

Asset Investment Planning (AIP) comprises models and/or tools that offer a structured approach to planning medium- and long-term asset investments, considering not only financial and technical factors but also environmental, social, and regulatory factors.

AIP tools enable:

- Prioritising investment projects based on risk, criticality and environmental impact.
- Evaluating alternatives for renovating, replacing or refurbishing assets based on life cycle cost criteria (LCC and Green-LCC).
- Simulating prospective scenarios up to 2030–2050, aligned with decarbonisation targets.

In this context, integrating environmental footprints, environmental costs, and circularity indicators becomes a key component in ensuring that investment plans meet both profitability and sustainability objectives.

7.2. Data flows and integration with AIP models

The procedure defines the incorporation of the environmental layer into traditional AIP models through:

1. Technical and operational data on assets (reliability, availability, physical condition).
2. Environmental data (carbon footprint, water footprint, circularity indicators).
3. Economic conversion of environmental impacts into costs (SCC, water cost, etc.).
4. Integration into investment decision models: Green-LCC, extended TCO, multi-criteria analysis.

In this way, each AIP model evolves from a financial/technical prioritisation tool to a comprehensive model for sustainable asset investment planning [7] [9].

7.3. Interfaces and usability

AIP models, tools, or applications should facilitate the straightforward interpretation of complex information. To this end, the following are proposed:

- Integrated dashboards: visualisation of economic, technical, and environmental KPIs in the same environment.
- Prescriptive alerts: notifications when an environmental indicator exceeds a defined threshold (e.g., excessive carbon footprint of a component, replacement ratio higher than planned).
- Scenario simulation: ability to evaluate maintenance alternatives under Green-LCC criteria [7].
- Automated reporting: generation of reports in accordance with standards (e.g. EU Taxonomy, Corporate Sustainability Reporting Directive (CSRD)).

7.4. Casos de uso demostrativos

1. Railway. Track and rolling stock maintenance.
 - Integration of sensors and algorithms for predicting rail surface corrugation [20].
 - Visualisation of the carbon footprint associated with grinding, rail replacement and reconditioning operations.
 - Dashboards comparing financial cost vs. environmental cost in component replacement [17].
2. Energy. Electrical substations.
 - Application of the Systemic Impact Factor (SIF) to prioritise critical assets considering environmental impact [13].
 - Integration of circularity indicators in transformers and switchgear.
3. Infrastructure. Bridges and roads.
 - Use of the Asset Health Index (AHI) extended with carbon footprint and circularity [8].
 - Predictive maintenance planning minimising long-term environmental costs.

8. PROPOSED PROCEDURE (SUMMARY)

A procedure has been designed to incorporate carbon and water footprints, environmental costs and circularity indicators into AIP tools. The procedure is summarised below in six phases:

Phase 1. Identification and modelling of the asset.

- Description of the asset in its digital twin (hierarchical structure, components, materials).
- Determination of critical maintenance operations.

Phase 2. Environmental data capture

- Collection of primary data (energy, water, materials, waste).
- Integration with secondary sources (emission factors, LCA databases).

Phase 3. Calculation of environmental footprints

- Application of ISO 14064 (CO₂) and 14046 (water).
- Automated calculation using algorithms implemented in the AIP.

Phase 4. Internalisation of environmental costs

- Monetisation of emissions and consumption using SCC and shadow pricing [7].
- Green-LCC (G-LCC) calculation.

Phase 5. Calculation of circularity indicators

- Definition of indicators (durability, reconditioning ratio, recycling).
- Automatic calculation based on digital maintenance records [17].

Phase 6. Integration into AIP and decision support

- Incorporation of KPIs into dashboards.
- Issuance of prescriptive recommendations based on extended SIF and AHI [13].
- Reporting aligned with EU taxonomy and SDGs.

Roles and responsibilities

- Asset manager: defines environmental limits and targets.
- Maintenance team: collects and validates operating data.
- Environmental team: ensures methodological consistency in footprints and costs.
- Digital team: integrates algorithms and visualisations into AIP.

9. IMPLEMENTATION OF ENVIRONMENTAL TOOLS IN THE CLOUD USING DIGITAL TWINS

The integration of carbon footprint, water footprint, environmental cost and circularity indicator calculations into Asset Investment Planning (AIP) tools requires not only calculation methodologies, but also robust digital support that allows for operational and scalable deployment. To this end, the project has implemented these tools within a cloud platform based on Digital Twin, deployed in Azure IoT Central.

This approach makes the Digital Twin the core where physical data, technical models and environmental indicators converge, ensuring an integrated and dynamic view of the asset. This ensures that ecological metrics do not remain a theoretical exercise, but are used in actual operations and investment planning.

9.1. Cloud architecture

The Digital Twin architecture has been structured according to international reference frameworks (RAMI 4.0 [23], ISO 23247 [24]). It has been implemented in a hierarchical system of digital devices in Azure IoT Central, characterised by four levels or structures:

- Physical level: real asset (e.g. power converters in one of the use cases developed).
- Level 1. Data ingestion: from sensors and monitoring systems. This ingestion can be direct in a more advanced process or simulated (as there is not yet any physical equipment to supply the information).
- Level 2. Data restructuring: organisation into virtual structures (complete equipment, subsystem, component).
- Level 3. Models and algorithms: execution of asset monitoring (AMM), asset behaviour (ABM), machine learning (AML), reliability (RAMS), health index (AHI) and life cycle cost (LCC) models. Environmental modules have also been incorporated here.
- Level 4. Interfaces and visualisation: interactive dashboards, exportable outputs in JSON and connection to Business Intelligence tools such as Power BI.

This modular architecture enables scalability (by extending digital twins to entire fleets), interoperability (with ERP, CMMS, and SCADA), and flexibility in integrating new environmental models without altering the overall structure.

9.2. Environmental models integrated into the Digital Twin

The Digital Twin is not limited to technical health and reliability indicators. By incorporating an environmental layer into the design, it integrates with existing models, enabling the calculation of:

- Carbon footprint (CO₂): real-time calculation based on energy consumption, materials and maintenance operations. This calculation is linked to the environmental LCC (Green-LCC), internalising the social cost of carbon (SCC).
- Water footprint: integration of direct and indirect water consumption, normalised with international factors (Water Footprint Network, ISO 14046).
- Environmental costs: monetisation of impacts through shadow prices and internalisation methodologies (SCC, water cost). This data is connected to the LCC & Corr_Cost module of IoT Central, so that technical degradation is translated into projected environmental cost.
- Circularity indicators: reconditioning versus replacement ratio, percentage of recycled materials and effective component life. These indicators are incorporated into the Asset Health Index (AHI) configuration, so that the environmental status complements the technical status.

With this integration, the Digital Twin becomes a comprehensive technical, economic, and environmental analysis system.

The practical implementation of this model on the cloud platform has been carried out in accordance with the methodological guidelines defined in González-Prida et al. [22], integrating the LCC-AHI-Environmental calculation into the LCC & Corr_Cost module of the Digital Twin. Thanks to this integration, the Azure IoT Central platform enables the automatic calculation and updating of economic and environmental parameters for each asset, based on real-time data from sensors and maintenance records.

This digitised model includes the automatic updating of spare parts, labour and energy costs, as well as the estimation of production and availability losses associated with each failure event. Similarly, the AHI is used to adjust failure frequency correction factors, enabling life cycle projections and environmental costs to be updated based on the equipment's operational status.

Furthermore, cloud integration enables the automation of the servitisation process, allowing organisations to adopt business models based on services and environmental performance, where a combination of these informs maintenance and investment decisions, incorporating technical, economic, and sustainability indicators.

9.3. Visualisation and exploitation of results

The Azure platform offers different interfaces that enable the practical exploitation of environmental indicators:

Online_View: live visualisation of consumption, emissions and environmental footprints, together with technical health indicators and failure modes.

- AHI_LCC_Corr_View: integrated dashboard that links the asset health index (AHI) with the total life cycle cost (LCC) and internalised environmental costs. It allows you to see how technical degradation simultaneously increases financial and ecological costs.
- PM & MM_View: consolidated view of the Intelligent Maintenance Plan, which includes comparative scenarios of economic and environmental impact for different maintenance strategies (preventive, corrective, predictive).

- Data export (JSON): results are generated in standard format and integrated into corporate Business Intelligence tools (Power BI), facilitating investment decision-making within the AIP framework.

In this way, environmental tools become operational KPIs within the same digital environment already used by operation and maintenance teams.

9.4. Benefits of cloud implementation

The implementation of environmental modules in a cloud-based Digital Twin provides concrete benefits:

- Centralisation: all technical, economic and environmental indicators are managed in a single digital environment.
- Scalability: the architecture allows coverage to be easily extended to more equipment, plants or infrastructure.
- Two-way feedback: data from the physical asset feeds into the digital twin, and simulations generate environmental recommendations that can feed back into the operation.
- Reduced uncertainty: thanks to the use of Hardware-in-the-Loop (HIL) and simulations, it is possible to calculate environmental footprints even in the absence of initial real data.
- Strategic alignment: the use of the cloud and BI interfaces facilitates integration with corporate sustainability policies and regulatory reporting (CSRD, EU Taxonomy).

The deployment in Azure IoT Central demonstrates that incorporating AIP environmental tools is not a theoretical concept, but a practical reality. The Digital Twin becomes the space where technical, economic, and environmental information converge, enabling investment decisions that are aligned with sustainability and digitalisation objectives.

In short, this implementation constitutes a milestone for the project, as it materialises in the cloud the methodological proposal developed in this deliverable, ensuring its real applicability in industrial and infrastructure environments.

10. VALIDATION AND EXPECTED RESULTS

10.1. Validation in case studies

The procedure has been tested in three representative sectoral contexts:

1. Railway sector

- Application in the maintenance of railway track repair machinery (tamping machines and profilers in the DFMAS project).
- Development of a digital twin that integrates the carbon footprint of rail grinding and replacement operations [17] [20].
- Validation by comparing scenarios: complete replacement vs. reconditioning, considering the savings from improving the carbon footprint and reducing the Green-LCC.

2. Energy sector (electrical substations and converters)

- Inclusion of the Systemic Impact Factor (SIF) to prioritise failures considering safety, reliability and environmental factors [13].
 - Results: better targeting of resources on equipment with greater combined technical and environmental criticality, reducing the risk of interruptions and associated emissions.
 - The LCC–AHI–environmental model [22], age systems. The practical application of this methodology has demonstrated the feasibility of integrating reliability, asset health and environmental cost data into a single digital environment, validating the combined approach of economic analysis and sustainability. The results obtained show significant improvements in the accuracy of life cycle cost calculations, as well as in sustainability-oriented investment decision-making.
3. Civil infrastructure (bridges and roads)
- Use of the Asset Health Index (AHI) extended with environmental parameters [8].
 - Reductions in annual emissions and water consumption were verified through decisions based on optimised predictive maintenance.

10.2. Monitoring KPIs

The procedure defines a set of Key Performance Indicators (KPIs) that enable its impact to be assessed:

- tCO₂e avoided per year.
- m³ of water saved per year.
- % of environmental costs internalised in the Green-LCC.
- % of components reconditioned versus replaced.
- Asset circularity index or rate (ICA).
- Compliance with reduction targets aligned with European and Spanish goals for 2030 and 2050.

10.3. Expected benefits

The application of the procedure defined in this deliverable is not limited to obtaining environmental indicators or generating new modules within the AIP tools. Its actual value lies in the benefits it brings to organisations, both in the short and long term, by integrating sustainability, efficiency and digitalisation into asset management. These benefits manifest themselves in several complementary dimensions covering environmental, economic, social and technological aspects, ensuring that investment and maintenance decisions are aligned with ecological and digital transition objectives. These benefits can be classified into four categories:

- Environmental: reduction of emissions and water consumption, alignment with climate neutrality.
- Economic: optimisation of the life cycle through reduction of hidden costs, increased resource efficiency [7].
- Social: increased transparency and accountability to stakeholders.
- Digital: incorporation of new layers of environmental intelligence into platforms through the use of AIP tools, reinforcing their role as digital twins as a maintenance 5.0 tool.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1. Conclusions

Firstly, the document has defined a standardised procedure for coherently integrating carbon footprint, water footprint, environmental costs, and circularity indicators into AIP models and tools. This procedure is based on recognised international methodologies, which ensure its robustness and applicability in different sectors.

Secondly, the methodological proposal combines regulatory, economic and digital approaches in a complementary manner. On the one hand, international standards such as ISO 14040, ISO 14044, ISO 14046, ISO 14064, and ISO 14067, as well as the GHG Protocol, have been incorporated. On the other hand, the economic assessment of impacts has been integrated through Green-LCC, which extends traditional life cycle analysis by internalising environmental costs. Finally, advanced digital technologies, such as digital twins, IoT, and artificial intelligence, have been introduced, facilitating the calculation, monitoring, and integration of environmental information into investment planning processes.

Thirdly, the validation of the procedure in real case studies (rail, energy and infrastructure) demonstrates not only its technical feasibility but also its practical usefulness. The results obtained reflect concrete benefits, such as significant reductions in CO₂ emissions, water savings and improved material circularity, as well as optimisation of the total cost of ownership. This improvement confirms that the methodology is not limited to a theoretical framework but can be applied in real operating environments with tangible results.

Ultimately, the proposed approach represents a significant step toward the convergence of the ecological transition and the digital transition in asset management. By incorporating environmental indicators into AIP models, organisations not only strengthen their ability to make more efficient investment decisions but also align those decisions with the decarbonisation and circular economy targets set for 2030 and 2050. This step represents a milestone in the evolution of Asset Management 5.0, where sustainability, economic efficiency and digitalisation converge within the same strategic framework.

With this document, the project complies with Deliverable A2.D4.2, providing a comprehensive, detailed and validated procedure for incorporating environmental criteria into AIP tools and apps, ensuring their alignment with the objectives of sustainability, efficiency and digitalisation in asset management.

11.2. Recommendations

Following the development of the procedure and its validation in various case studies, it is necessary to offer a series of recommendations to guide the practical implementation of this framework in organisations that manage assets. These recommendations not only seek to facilitate the progressive adoption of the methodology, but also to ensure that the integration of environmental criteria into AIP models is carried out with rigour, continuity and a long-term vision. Furthermore, the aim is for entities to maximise the value obtained, both in terms of economic efficiency and sustainability, by aligning their investment strategies with the climate neutrality and circular economy targets set by the European Union for 2030 and 2050. We have divided these recommendations into six groups:

- Progressively scale up the implementation of the procedure, starting with critical assets and subsequently extending it to the entire organisation.

- Strengthen data quality through sensorisation, traceability and digital auditing strategies.
- Adopt internal shadow pricing policies to raise awareness within the organisation of the real cost of emissions and consumption.
- Incorporate digital sustainability training and education for maintenance and asset management teams.
- Promote interoperability with other reporting standards (CSRD, EU Taxonomy, SDGs) to maximise the usefulness of environmental information.
- Develop prospective simulations towards 2050 to assess the contribution of maintenance operations to climate neutrality objectives.

Based on the results obtained in the studies carried out, the following recommendations are proposed to improve the environmental performance of the railway system and facilitate the integration of sustainability criteria into the design, operation and planning of railway machinery:

1. Incorporate G-LCC as a support tool in technical and strategic decision-making, both in the design phase and in the evaluation of technological alternatives, to identify opportunities for reducing environmental impacts from a comprehensive perspective.
2. Prioritise the use of recyclable materials with low environmental impact in the manufacture of locomotives and carriages, promoting eco-design and the selection of suppliers that comply with sustainability and emissions traceability criteria.
3. Optimise energy consumption during operation through the progressive electrification of the railway fleet, the improvement of traction system efficiency and the integration of renewable energy sources into the supply infrastructure.
4. Reduce the water footprint associated with maintenance and cleaning processes by implementing water reuse technologies, dry cleaning systems, and efficient water resource management in railway facilities.
5. Establish continuous environmental monitoring systems to record and analyse key indicators such as GHG emissions, energy consumption, waste generation and water use, facilitating traceability and constant improvement of environmental performance.
6. Promote collaboration between public administrations, railway operators, manufacturers and research centres to develop standardised methodologies, sectoral databases and digital tools that facilitate the application of G-LCC in the railway sector.

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