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LIFE-CYCLE STRATEGIES FOR SUSTAIBLE MAINTENANCE IN TUNNEL MANAGEMENT

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Abstract

The research proposes an approach based on the Life Cycle Assessment (LCA) methodology to evaluate the environmental impact, which becomes one of the indicators for the design choice among the possible engineering solutions, in addition to the technical and economic one, for tunnel maintenance. The paper presents the first results of applying LCA on a typical tunnel section of Italian motorway, comparing three types of maintenance interventions targeting crack-type defects in concrete tunnels. The aim is to gather data on their environmental impacts to be used in the decision-making process during the planning phase of tunnel maintenance activities.

Introduction

The significant contribution of the construction industry to greenhouse gas (GHG) emissions has triggered attention for environmental impact mitigation technologies in both built environment and highway construction (Ozcan-Deniz et al., 2017). The buildings and construction sector, in fact, accounts for approximately 37% of global GHG emissions, including those from energy and process-related sources (IEA, 2023). It is essential to move to a circular economic (CE) model to promotes a sustainable built environment rehabilitation with increased efficiency for construction resources and waste minimization at construction stage and end of life (Marchionni et al, 2024). The increasing interest in effectively reducing environmental impacts has led highway construction practitioners to the search for delivering projects in a resource-efficient, cost-effective, and environmentally friendly manner (Manoj et al., 2012). In recent years, the study of literature shows a growing interest in the containment of environmental impacts related to the construction and/or maintenance phase of infrastructure using the Life Cycle Assessment (LCA) approach. In fact, the LCA methodology, applied according to ISO 14040 and ISO 14044, allows the evaluation of environmental impacts of product or process starting from raw material(s) extraction to manufacture/production/construction to operation and maintenance to final disposal (Ye et al., 2017; Cucchiella et al, 2024), across various indicators. A lot of studies assess the emissions and energy consumption during the construction stage: (Damián et al., 2022) estimated the environmental impact of the construction of 1 km of double-track high-speed railway tunnel for five different Rock Mass Rating classes using the LCA methodology. (Wang et al., 2015) proposed an empirical method to estimate carbon dioxide (CO2) emission generated from highway construction based on four real projects in southwest region of China, and the results show that over 80 percent of the CO2 emission was generated from raw material production. (Costel et al., 2022) applies LCA methodology to assess the environmental impact of tunnel construction, focusing on materials like concrete, steel, and excavation processes. (Aryan et al., 2023), after analysing 67 LCA studies on road pavements and road infrastructures, found that ~76% of them considered material and construction phase and assessed the impacts in terms of only two impact categories: global warming potential and energy demand. (Noland et al., 2015) made a GHG life-cycle assessment for a large highway reconstruction project in New Jersey and the GASCAP model was used to determine the total life-cycle GHG emissions associated with the materials used, construction equipment, mobilization of resources for the project, traffic disruption during construction, and materials used for life-cycle maintenance. However, there are still few studies and methodological approaches concerning the optimisation of the maintenance and use phase of motorway constructions (Frisiani et al., 2024).
Therefore, this paper aims to fill this research gap, applying the LCA methodology to the case study of an Italian motorway tunnel section, evaluating three different maintenance strategies.

Case Study

Italy's motorway infrastructure, largely developed between the 1960s and 1970s, is experiencing significant deterioration, requiring continuous monitoring and efficient management to ensure safety and sustainability.
In this context, the 'Gruppo Autostrade per l'Italia S.p.A.' (Gruppo ASPI) plays a key role, managing a motorway network of approximately 3,000 km across 15 regions and

60 provinces. This network includes over 4,200 bridges and viaducts, as well as 595 tunnels. Given the aging infrastructure, optimizing maintenance strategies while minimizing environmental impact has become a pressing challenge. Infrastructures in Italy are currently facing a significant phase of deterioration, characterized by the aging of critical structures such as bridges, roads, tunnels and public transport systems, which require urgent attention and maintenance. Given recent events, new guidelines have been developed, precisely the DM 247/22 “Linee Guida Per La Classificazione E Gestione Del Rischio, La Valutazione Della Sicurezza Ed Il Monitoraggio Delle Gallerie Esistenti” (Ministero delle Infrastrutture e della Mobilità Sostenibili, Consiglio Superiore dei Lavori Pubblici, 2022), which defines a methodology for classifying the risk associated with the severity of structures. Tunnels are categorized into risk levels based on this severity, determining the required attention and interventions. The guidelines provide a procedure for managing activities aimed at ensuring the safety of existing road tunnels, to prevent damage levels that could impact the safety of the structure and, more broadly, the entire infrastructure, making the risk acceptable.

The framework proposed by the guidelines aims to prevent potentially dangerous situations, planning informed preventive maintenance actions.

In this context, the decision-making phase becomes crucial, as it is necessary to determine where, how, and when to intervene through maintenance actions. Considering the current context of climate change, resource scarcity and the growing demand for environmentally responsible practices, it is crucial to integrate sustainability into the decision-making phase. This ensures that maintenance interventions not only address immediate structural concerns but also minimize environmental impacts and reduce carbon footprints.

The following study aims to provide LCA studies for different maintenance interventions to integrate environmental sustainability as a key decision-making indicator fostering a balance between technical performance, economic feasibility, and environmental stewardship.

The study analyses the environmental impact of three specific, localized, and relatively small-scale maintenance interventions using an LCA approach.

The previously mentioned guidelines (Ministero delle Infrastrutture e della Mobilità Sostenibili, Consiglio Superiore dei Lavori Pubblici, 2022), particularly Annex B “Catalogo dei difetti” (“Defect Catalogue”), not only provide a description of the various categories and types of defects that can occur in a tunnel but also assign each defect a unique identification code. This code aims to standardize defect detection and recording, facilitating data management and comparison.

The interventions selected for this paper are all linked by the type of defects they address. Specifically, the defects targeted by all the selected intervention types involve issues with the tunnel’s structural elements and geometry, primarily characterized by the presence of cracks. The types of cracks considered are:

- longitudinal cracks along the lining [code 3.1]: cracks oriented parallel to the longitudinal axis of the tunnel;
- diagonal cracks [code 3.2]: cracks oriented diagonally with respect to the tunnel's longitudinal axis;
- vertical cracks [code 3.3]: cracks oriented perpendicular to the tunnel's longitudinal axis;
- shrinkage cracks [code 3.4]: thin cracks on unreinforced concrete, with a width rarely exceeding 1-2 mm;
- curvilinear cracks [code 3.5]: cracks characterized by a uniform curved pattern, resembling a crescent shape.

The maintenance interventions analysed in this study were provided by the engineering company TECNE, a consultant for Gruppo ASPI. Among the various maintenance interventions provided by the team, the study focuses on interventions classified as “detect and repair works” under the acronym IMS (Extraordinary maintenance intervention, in Italian: “Intervento di Manutenzione Straordinaria”). Three specific types of interventions were selected among the IMS interventions available, all of which are applicable to the defects previously outlined. The interventions analysed are the following:

- IMS 4B: repair cracks by injecting epoxy resins into drilled holes, sealing the crack with epoxy adhesives, and final surface restoration with trowel-applied mortar.
- IMS 4C: stitching of cracks using steel bars inserted into drilled holes, combined with epoxy resin injections, crack sealing and surface reinforcement
- IMS 5A: reinforcement through the application of FRCM systems (fiber-reinforced cementitious

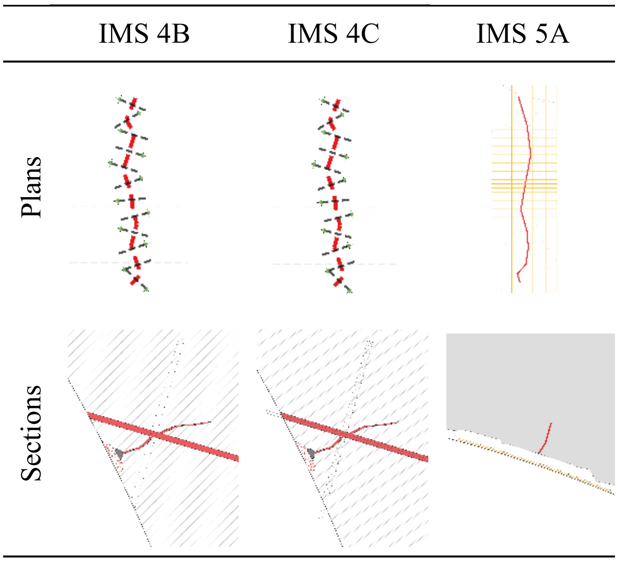

Figure 1: Maintenance interventions – Plans and Sections

matrix), focusing exclusively on linear defects to ensure comparability with IMS 4B and 4C.

All the interventions, as previously mentioned, are applicable to common categories of defects, and for this reason, they can be compared. However, it is necessary to make some clarifications. The first two interventions (4B and 4C) are almost identical, with the sole difference being that the second one (4C) involves the addition of rebar. The third intervention (5A) takes a completely different approach compared to the other two. Notably, this third intervention was designed for both areal and linear applications. However, to ensure comparability with the other two, only procedures for linear application were considered.

Materials and Methods

The methodological framework adopted for the comparative study is given by the standards UNI EN ISO 14040 and UNI EN ISO 14044 (ILCD, 2010). Said standards define the four inter-related stages of a LCA:

1. Goal and scope definition: the stage consists in the definition of the purpose of the study, the functional unit, the system boundaries, and other limitations or assumptions.
2. Inventory analysis: definition of input and output flows related to the system.
3. Impact assessment: aggregation of inventory results, assessment of environmental impacts using scientific models.
4. Interpretation: analysis of the results.

To conduct the analysis the authors employed SimaPro 9.3.0.2 and the Ecoinvent 3 database, both compliant with UNI EN ISO standards 14040 and 14044.

Goal and Scope Definition

The objective of this LCA analysis is to evaluate the environmental impact of three types of maintenance interventions targeting crack-type defects in concrete tunnels. The aim is to gather data on their environmental impacts to be used in the decision-making process during the planning phase of tunnel maintenance activities. The maintenance interventions, previously described in the preceding chapter, will hereafter be referred to by the acronyms: IMS 4B, IMS 4C and IMS 5A.

The three interventions under consideration are applicable to cracks present on the inner surface of tunnels. These are therefore linear maintenance applications, which is why the chosen functional unit is the meter of crack, directly corresponding to the length of the specific defect being addressed.

System boundaries have been selected according to the life cycle stages defined in the UNI EN ISO 15978:2011 norm, to evaluate the impacts related to the "product" stage (A1-A3) and the "construction process" stage (A4-A5). This approach to boundaries definition is coherent with the scope of the study and may be integrated in further studies as the maintenance stage (B2) of a tunnel or a chunk of it according to the same norm.

Some assumptions were in order since the assessment is not based on a specific maintenance scenario. The transport distances have been all considered from a point A (production) to a point B (construction site) distant 250 km. In all cases the cracks have been considered at a height that would require the use of an elevation platform to intervene.

Inventory Analysis

Life cycle inventory (LCI) is defined as the quantification of the inputs and outputs in each life cycle stage of the product. This stage is often the most time-consuming part of any LCA study and involves collection and compilation of data on elementary flows from all processes considered within the system boundary.

This study was based on data of the three different case studies provided by the Italian engineering company Tecne. The first step was to identify the main processes involved in the three maintenance interventions and all the materials and equipment associated with them. Table 1 outlines the key steps defining each intervention, while Table 2 provides a detailed list of the materials involved, which were subsequently selected into the database and used for the calculations.

The study focuses on three generic maintenance interventions not tied to any specific case study. As a result, the site location was not defined, and the transport distance was assumed to be 250 km (approximately one-fourth of the maximum distance between two motorway exits). As for the consumption of the on-site construction equipment the values have been derived from previous studies (Frisiani et al., 2024) and corrected to fit the

Table 1: Interventions main construction stages

Solution	Construction Stages
IMS 4B	- Surface preparation - Execution of micro-drillings with a diameter of 32 mm and a length of 60 cm, spaced every 40 cm and inclined at 45° - Injection of epoxy resin through PVC tubes - Sealing and closing of holes
IMS 4C	- Surface preparation - Execution of micro-drillings with a diameter of 32 mm and a length of 60 cm, spaced every 40 cm and inclined at 45° - Insertion into the perforations made of a steel bar with a diameter of 16 mm. - Injection of epoxy resin through PVC tubes - Sealing and closing of holes
IMS 5A	- Surface preparation - Application of a layer of MX-PBO concrete inorganic matrix - Installation of reinforcement PBO-Mesh plication of the second layer of inorganic matrix

specific operations related to the different type of interventions.

Since the starting data didn't consist of primary data on input and outputs related to the individual material and processes each item was reconducted to and LCI voice contained in the Ecoinvent 3 database (*Table*). Said database was selected since it is widely considered as the industry standard (Tefa et al., 2022) (Huang et al., 2015).

Table 2: Inventory voices included in the analysis

Solution	Material/ Process	LCI voice	Unit	q
IMS 4B	Epoxy resin, density 1.14 kg/l	*Epoxy resin, liquid {RER}| market for epoxy resin, liquid| Cut-off, U*	kg	3,45
	Epoxy resin, density 1.72 kg/l	*Epoxy resin, liquid {RER}| market for epoxy resin, liquid| Cut-off, U*	kg	1,38
	Transport (250km)	*Transport, freight, lorry, 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6| Cut-off, U*	kgkm	1207,5
	Construction equipment	*Diesel, burned in building machine {GLO}|market for|Cut-off, U*	kWh	7,4
IMS 4C	Epoxy resin, density 1.14 kg/l	*Epoxy resin, liquid {RER}| market for epoxy resin, liquid| Cut-off, U*	kg	1,725
	Rebar B450	*Reinforcing steel {GLO}| market for| Cut-off, U*	kg	5,875
	Epoxy resin, density 1.72 kg/l	*Epoxy resin, liquid {RER}| market for epoxy resin, liquid| Cut-off, U*	kg	1,38
	Transport (250km)	*Transport, freight, lorry, 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6| Cut-off, U*	kgkm	2245
	Construction equipment	*Diesel, burned in building machine {GLO}|market for|Cut-off, U*	kWh	7,4
IMS 5A	Concrete 40MPa	*Concrete, 40MPa {RoW}| market for concrete, 40MPa | Cut-off, U*	mc	0,008
	PBO mesh	*Carbon fibre reinforced plastic, injection moulded {GLO}| market for carbon fibre reinforced plastic, injection moulded | Cut-off, U*	g	126
	Transport (250km)	*Transport, freight, lorry, 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6| Cut-off, U*	kgkm	3831,5
	Construction equipment	*Diesel, burned in building machine {GLO}|market for|Cut-off, U*	kWh	19,8

Impact Assessment

The selection of impact assessment method was found to be influenced by the country in which LCA study was performed. For example, the LCA studies carried out in Switzerland predominantly use Ecological Scarcity indicator (Gschosser and Wallbaum, 2013). The studies in Italy consider two different impact assessment methods. ECO-Indicator 99 for assessing the land use and ecotoxicity; and CML 2 BASELINE 2000 for assessing global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical oxidants creation potential (POCP), abiotic depletion potential of fossil resources (ADP_f), abiotic depletion potential of elements (ADP_e) and human toxicity potential (HTP) (Cantisani et al., 2018). Studies in Europe mostly perform their LCA studies as for European standard (EN 15804). CML method is preferred in studies performed in USA. (Moretti et al., 2018) recommends the use of wide range of impact categories in LCA studies for performing comprehensive and unbiased analysis.

The method of choice for this study is the EN15804+A1 V1.00, considering the following impact categories: GWP, ODP, AP, eutrophication potential, freshwater (EP-fw), eutrophication potential, marine (EP-mar), eutrophication potential, terrestrial (EP-ter), photochemical ozone formation (POCP), ADPF, ADPE, water use (WDP).

The choice of said method is motivated by the will to obtain results that are coherent with other studies regarding the Italian highway infrastructure, in particular (Frisiani et al., 2024), given the similarity in subject matter.

Emissions defined in the LCI phase are associated by the software with impact categories according to the selected calculation method.

Interpretation

The environmental impacts of the three intervention methods considered are aggregated by impact category in Table 3.

Table 3: Environmental impacts, EN 15804+A2 method V1.00

CAT.	UM	IMS 4B	IMS 4C	IMS 5A
GWP	kg CO2 eq	2,71E+01	3,02E+01	2,09E+01
ODP	kg CFC11 eq	4,15E-06	3,57E-06	2,00E-06
AP	mol H+ eq	1,29E-01	1,40E-01	1,40E-01
EP-fw	kg P eq	7,96E-03	1,04E-02	4,36E-03
EP-mar	kg N eq	3,16E-02	3,68E-02	4,34E-02
EP-ter	mol N eq	3,33E-01	3,78E-01	4,69E-01
POCP	kg NMVOC eq	1,24E-01	1,46E-01	1,30E-01
ADPE	kg Sb eq	2,98E-04	2,32E-04	4,53E-05

ADPF	MJ	4,98E+02	4,60E+02	2,45E+02
WDP	m3 depriv.	1,19E+01	1,18E+01	2,34E+00

The comparison between the three possible intervention methods Figure 2 shows that IMS 5A is characterised by a better behaviour in all but two impact categories (EP-mar, EP-ter) granting a significant increase in sustainability in relation to GWP (20-30%), EP-fw (35-58%), ADPE (62-85%), ADPF (43-51%), WDP (79-80%).

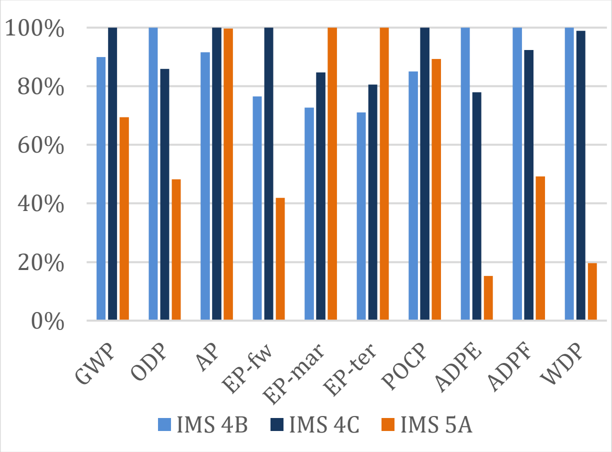

Figure 2: Environmental impacts, EN 15804+A2 method V1.00

The joint evaluation of IMS 4B and 4C (whose difference is in the use of rebars in the latter one) shows better results in favour of IMS 4B, except for ODP and ADPE.

Overall, the solutions where epoxy injections have been employed results in an higher percentage of impacts linked to materials (Figure 3 and Figure 4), while in IMS 5A the use of a concrete matrix in wich is situated a PBO mesh makes it less preponerant on the overall impact of the intervention, increasing the contribution of transports and on-site operation (Figure 5).

Conclusions

This study analyses the environmental impacts of three small-scale maintenance interventions using an LCA approach, that can all be applied to the same category of defects of Italian's motorway tunnel.

The research underscores the importance of integrating environmental sustainability as a central criterio in maintenance interventions' planning and decision-making phases. LCA offers an objective framework to balance technical performance, economic feasibility, and environmental impacts.

The analysis demonstrated that the IMS 5A intervention is significantly more sustainable than IMS 4B and 4C in nearly all impact categories considered. In particular, it shows a reduction in GHG emissions and the consumption of mineral and fossil resources, highlighting this solution's potential to improve tunnel maintenance interventions' ecological footprint.

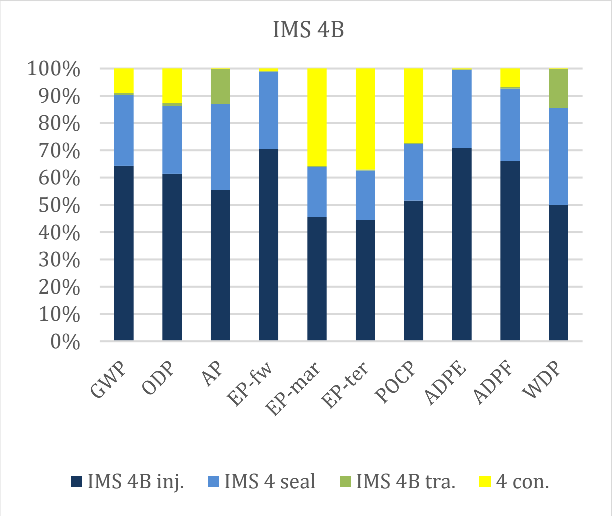

Figure 3: IMS 4B, contribution, EN 15804+A2 method V1.00

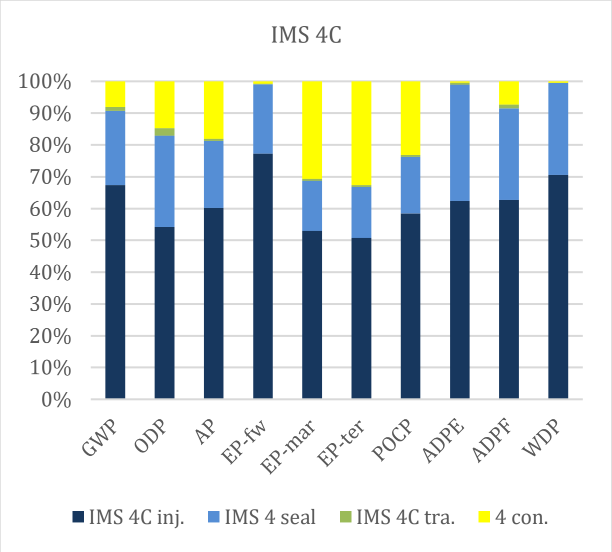

Figure 4: IMS 4C, contribution, EN 15804+A2 method V1.00

However, for LCA to serve as a genuinely effective decision-making tool in infrastructure management, it must be specifically designed and applied to reflect the scale and complexity of real-world interventions and some questions remain open for further investigation.

For instance, it would be interesting to analyze the effect of longer transport distances, which could diminish the environmental advantage of the IMS 5A system due to its higher reliance on transportation. Another possible avenue for exploration could focus on on-site operations, as the graphs clearly indicate that the 5A system is

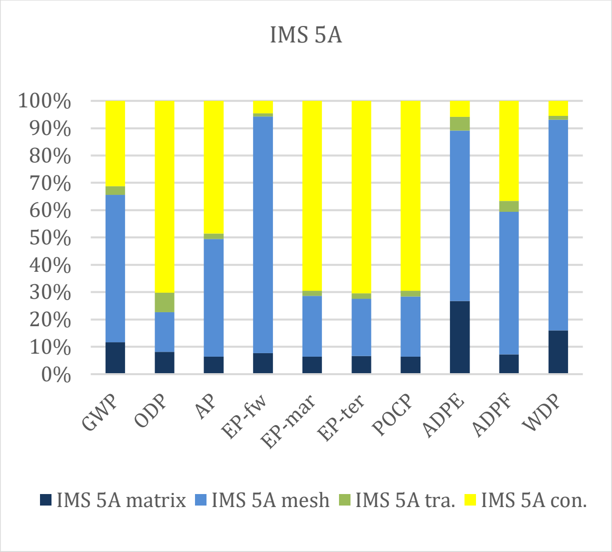

Figure 5: IMS 5A, contribution, EN 15804+A2 method V1.00

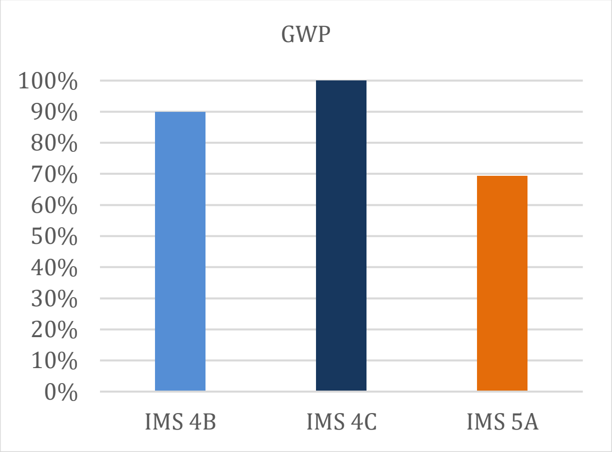

Figure 6: GWP emissions, comparison

significantly influenced by these activities (Figure 5). It would be valuable to hypothesize and evaluate alternative, innovative construction methodologies to determine whether they could alter the overall results and further enhance sustainability. Furthermore, it is essential to underline that maintenance decisions are typically based on entire tunnel segments, often spanning approximately 20 meters, rather than based on individual localized defects. Therefore, environmental impact assessments should also aim to adapt to this reality by evaluating broader sections of tunnels containing a variable number of defects, potentially of different types. Such an approach would require a shift in the functional unit of analysis, transitioning from single linear cracks to entire tunnel segments. This shift could significantly influence the comparative outcomes. For instance, IMS 5A, adopted for more extensive applications, requires additional materials and processes, which might alter its environmental profile. By adopting a segment-based perspective, future studies could provide results that are both environmentally comprehensive and more aligned with the practical realities of maintenance planning.

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Author contributions

Paper Conceptualization and Methodology V.V., M.R., F.Cu. and C.M.; Writing—original draft preparation V.V., C.M., P.A.R.C. and F.Ca.; Software F.Ca., C.M., P.A.R.C.; Supervision V.V., M.R., F.Cu. All authors have read and agreed to the published version of the manuscript.

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