University of Naples Federico II

Department of Civil, Construction and Environmental Engineering

Doctoral research in

Civil Systems Engineering

Cycle XXXV

BIM-based system for sustainable road pavement maintenance

Coordinator

Prof. Eng. Andrea Papola

Candidate

Eng. Cristina Oreto

Tutor

Prof. Eng. Francesca Russo

Prof. Eng. Salvatore Antonio Biancardo

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1 Introduction

Road infrastructures and their management processes are key elements to foster the economic and social development of communities [1]; indeed, road pavements maintenance management involves crucial actions to define the strategies that keep the structural and functional characteristics of the pavement above certain thresholds, as well as minimizing life cycle costs [2, 3]. Moreover, the management of road pavements to keep the functional and structural performance over predefined thresholds throughout their service life entails the consumption of large amounts of natural materials and exhaustible resources, as well as the generation of high volumes of waste, affecting the environment via multiple damage pathways [4].

The improvement of the material's mechanical performance, the reduction of waste in landfills, natural aggregates' extraction, and the energy and cost requirements to produce, build, and maintain asphalt pavements are themselves indicators of the sustainability of a solution. Anyhow, the quantitative analysis of the environmental impacts of pavement systems along the entire life cycle, known as the Life Cycle Assessment (LCA) procedure, is a key element to prevent the shifting of negative impacts on the environment from one stage of the life cycle to another and help decision makers to compare multiple solutions and select the one that has the lowest impact on the environment. On the other hand, Life Cycle Cost Analysis (LCCA) can be applied for the evaluation of the economic performance of a pavement over its entire life, balancing initial monetary investment with the long-term expense of owning and operating the pavement system.

Neither LCCA nor LCA are synonymous with a sustainability assessment but they provide critical information and metrics, which, when complemented with other appraisal techniques, can be used either to find the most cost-effective paving solutions to reduce environmental impacts or, at a higher decision level, to measure progress towards sustainability targets. One of the techniques that can further extend the achievements obtained through the conjoint application of the aforementioned life cycle-based approaches is the multiobjective optimization (MOO) technique. MOO is well suited to incorporating environmental concerns in the optimization of sustainable processes, since it allows them to be treated as decision-making objectives to be optimized in conjunction with the traditional economic-based criteria. Therefore, by embracing these concepts and incorporating them into decision-support systems (DSSs) for pavement management, those in charge of deciding how sustainable pavement systems will be tackled, will be in a much better position to adapt and advance current pavement management practices towards enhancing pavement sustainability [5].

The management of road pavement maintenance processes is articulated according to the concept of predictive maintenance, which requires the integration of Pavement Management Systems (PMSs), consisting of the set of rules and actions that support decision makers in identifying the optimal interventions, with tools for monitoring, analysing and forecasting performance over time that ensure the maintenance of an adequate level of service of the road pavement [6].

Proper pavement maintenance planning is a strategic approach to the optimal conservation of resources, capital spending, risk control, performance preservation and stakeholder satisfaction. The best way to face this kind of challenges efficiently at different operational and strategic levels is to collect and run analytics on key data systematically to create business intelligence [7].

As emerging technologies are spreading rapidly through the construction industry, researchers are attempting to facilitate decision-making by incorporating multiple analyses in an automated context that supports infrastructure project, construction, management and disposal.

The digitalization of linear infrastructure projects can be nowadays supported by workflows that improve not only the quality of the deliverables but also the efficiency of the way they are developed, cultivating communication between project participants. In this context, more and more digital-oriented tools and technologies are supporting construction and maintenance processes of road infrastructures; Building Information Modelling (BIM), among other approaches, can enumerate several advantages, such as the earlier detection of omissions and errors, improved productivity, structures simulation and analysis, improvement of communication between the actors of the process through more informed participation and data sharing. However, its recent adoption in the infrastructure field and the peculiar complexities related to linear assets management still significantly hinder further developments and adaptations to fully make the most of the listed benefits [8].

For this purpose, the Infrastructure-Building Information Modelling (I-BIM) processes can be aimed at the creation of suitably computerized models (e.g. mechanical performance, distress data, degradation curves), supported and updated continuously and collaboratively by the actors of the BIM process during the useful life of the work [9].

There is now no argument that BIM is and has to be applied and viewed as something beyond just the 3D model. Even though it can be considered as the central core of any project, the part that provides the most return to professionals in terms of investment has to be considered the organizational one related to data. The initial investment in training and resources is later compensated by the increased quality of project deliverables and especially improved control and management of the assets in their operation life.

One of the major demands when it comes to linear infrastructure projects is related to the organization of all the data associated and its conveyance between all project participants (interoperability of information) in a streamlined way. These projects encompass a great amount of information (big datasets) that originates from manifold sources, often not properly organized and stored, leading to lack of organization.

The present work aims to develop a Pavement Information Model specifically targeted at improving the sustainability of road pavement maintenance operations through some automated BIM-based tool that automatically provide a structural, cost and environmental assessment of the solutions with a life cycle perspective.

2 The concepts of sustainability and circular economy

The concept of sustainable development emerged in the 1980s and refers to the balance between preserving the planet and meeting human needs [10]. The Brundtland Report [11] explains the same term simply as a development pattern that "meets the needs of the present without compromising the ability of future generations to meet their own needs".

What we now know as sustainable development has actually evolved through time as an integrated concept, an umbrella under which a number of related issues can be gathered to reach the final goal of sustainability. In the same context, sustainability is the ability of a system, human, natural or mixed, to show resilience and adaptation capabilities to endogenous or exogenous change indefinitely. Therefore, to achieve sustainability, sustainable development is required [12].

Many efforts have been dedicated to understand what is being studied and proposed on sustainability through theoretical and applied studies, objectives and challenges that aim to that find way to achieve the goal of sustainability.

According to Sartori et al. [13], the key features that can be associated to the concept of sustainability may be summarized in the following actions:

- discussions on the three spheres of sustainability, i.e. environmental, economic and societal to prompt environmental change, sustainability policies, improvement of the global living standards, planning and communication;
- development of indicators and models to quantify the different spheres of sustainability, as well as development of tools to evaluate the sustainability of products and systems;

- search for causality links between environmental, economic and social dimensions of sustainability.

The main elements of the Circular Economy (CE) paradigm consist of using renewable energy sources and materials, extending the useful life of each product, creating shared data platforms, reusing and regenerating, rethinking products; the CE model has been created to address the sustainability needs of the planet and offer businesses an opportunity in terms of competitiveness, innovation and job creation, creating value for companies and their customers.

As CE is necessary today to promote the goals of sustainable development; the CE elements are not independent to each other, but their synergies, relations and interactions exist and should be further developed and studied. Sustainability goals require connections between multiple scientific areas to overcome the current technological limits; overcoming such limits requires new policies (e.g. public procurements), technological advancements (e.g. new recycling and waste management solutions), engineering technologies (e.g., waste management, water recycle, wastewater treatment and reuse, use of renewable energies), business models, as well as the introduction of new product labels to make managing bodies and consumers conscious about CE.

One main task of CE is to maintain the value of products and materials for as long as possible, minimising the production of waste and the consumption of resources to produce new ones. According to this concept, products should be used again at the end of their service life, to create new value instead of being disposed of. Generating new value from old/end-of-life products can bring major environmental, as well as economic benefits, contributing to job creation, growth and innovation.

In the long term, applying CE models prompts both competitiveness and sustainability with a series of practical implications, such as saving costs for European industries and administrations, preserving resources, with particular reference the increasingly scarce ones, unlocking new business opportunities, exporting cleaner products around the world, creating new jobs and, ultimately, creating new opportunities for social sustainability, meaning integration and equity.

An indispensable component of the European Union's efforts to develop a sustainable and competitive economy is the transition to a CE system, in which the materials and energy used to manufacture products maintain their value for as long as possible, waste is minimized and the minimum amount of resources are used.

According to a recent study on the CE, the European objectives constitutes a "surprising" model of waste management aimed at the creation of value with its production and disposal system.

In 2012, for example, only 40% of waste materials was recycled or reused, while 60% was deposited in landfill or incinerated. In terms of value, Europe has lost 95% of its material and energy value, while the recycling of materials and energy recovery from waste has recovered only 5% of the original value of raw materials [14].

The transition to a CE therefore responds to both an environmental and an economic logic. It could in fact lower pressures on the environment, with positive effects on human health, ecosystems and biodiversity. By way of example, according to the Commission's estimates, the full implementation of the European waste management objectives would reduce sea pollution by 27% by 2030 [15].

It could also increase the security of energy supplies, since the EU currently imports roughly half of the resources it consumes in raw materials equivalent. In addition, businesses would have the potential to make savings on materials expenses (between 250 and 465 billion euros per year, or between 12% and 23% of materials expenses, according to the Ellen MacArthur Foundation [16]) as well as to benefit from organizational innovations and produced requests.

In order to speed up the transition to a CE model, it is necessary to intervene at all stages of the value chain of products, starting from the extraction of raw materials up to the design of materials and products, from the production, construction and distribution to the operating life of products, from the maintenance, repair, remanufacture and reuse to the application of new recycling and sustainable waste management practices.

One particularly phase of the life cycle of a product that should embrace the principles of the CE model is the design phase. The development of a product is based on a series of decisions, whose driving principles will surely affect the sustainability of the product during its whole life cycle. Therefore, appropriate preliminary assessments should be carried out to predict future different possible market and decision-making scenarios to assess the environmental and economic sustainability requirements. The optimum way to achieve sustainability during the design phase is following the principles of “eco-design” through the use of tools to assess multiple sustainability spheres that the production, maintenance and end of life phases entail.

The first principle to apply within a sustainable product design process is the rationalization and efficiency increase in the use of raw material resources, replacing non-renewable materials with renewable or recycled ones. The need is to "create" new materials that contemplate sustainability and circularity. Knowing the environmental and social implications of the materials and their production processes is essential to avoid design choices that will not favour the circularity of the life cycle.

Recyclability is an important factor that serves to facilitate the recovery and recycling of components and related materials, mainly avoiding multi-material sub-assemblies that will pose difficulties to recycling once the product has reached its end-of-life stage.

Improving the recycling rate of a product system is not the only way to prompt the sustainability of a product/system; in particular, efficient maintenance actions must be encouraged throughout the service life to allow the extension of the life cycle of the product itself, looking in particular for solutions that make products easily recyclable, taking as a reference the European legislation [17]. Recycling processes should aim to slightly alter the characteristics of the materials so that new reuse is allowed, compensating for a natural reduction in the quality of end-of-life materials and the relative lower economic value of the same.

This reflects on the need to only produce what can actually be "recycled": in the new CE paradigm, no more waste is generated that cannot be recycled or residues that cannot be reused in the same or in other production cycles.

2.1 Applying sustainability concepts to public bids

The Green Public Procurement (GPP), thanks to the provisions of the Procurement Code on the mandatory application of the Minimum Environmental Criteria (MEC), has become one of the main European environmental and production policy tools aimed at the integration of sustainability concepts in public bids, the reduction of environmental impacts, the rationalization of public spending, the promotion of virtuous companies from an environmental point of view. Indeed, the strategy of influencing the market through the introduction of sustainability requirements on the demand side stimulates qualification and innovation paths by companies, strengthening their competitiveness.

Thanks to GPP strategy, enhancing the quality and performance of products, their energy efficiency during use, safety in terms of limits to the presence of hazardous substances, the recycled content, repairability, durability of the products themselves, and more environmental impacts are reduced, but some economic indicators are improved: both by rationalizing public spending, and by encouraging new economic activities that deal with aspects and issues valued by MEC (repair and recovery, use of recycled materials, energy replacements and matter coming from non-renewable sources with those coming from renewable sources, enhancement of the bio-economy, etc.).

It therefore becomes strategic to ensure that there is full application of this tool by the Public Administration (PA). The powerful market lever represented by public purchases can become one of the main tools for directing production towards circular economy models. In fact, for example, while the MECs on the "urban waste management service" enhance the quality of separate collection, other MECs stimulate the demand for products made with materials derived from separate collection.

In general, it should be emphasized that MECs have complementary and synergistic prescriptions. Their joint application allows for the simultaneous implementation of the various indications referred to in all the Communications of the European Commission, in particular those on the circular economy and the efficient use of resources. With the new procurement code, the issue of the cost of a product/service must be referred to the cost along the life cycle (the so-called Life cycle costing), which includes in addition to the costs of using the product and its disposal also those related environmental externalities. The issues related to "circularity" must, therefore, also be addressed in the tender by highlighting the lower costs of products that better meet the objectives of the circular economy.

2.2 Measurement and communication of the sustainability of a product

Measuring the circularity of a product or service must be the goal of all companies to take note of the quantities and types of natural resources used, among other things, in terms of:

- renewable and non-renewable;
- recycled and recyclable;
- biodegradable and compostable;
- sustainability of the product considering the economic, environmental and societal spheres.

Measuring sustainability is a question of creating an "input-output" budget considering the entire life cycle of the product and not just the production stages. The approach in the measurement of sustainability should consider the types of resources to be inventoried (raw materials and energy resources), and the degree of detail of the analysis (e.g. involving or not the suppliers or other subjects involved in the supply chain). The inventory phase of a sustainability assessment must be very accurate to avoid approximations that can create significant errors that propagate throughout the calculation methodology. The inventory phase may be eased considering that the data useful to fill up the inventory itself are often already in the possession of the companies as they represent the specifications of each individual product. In addition to the production data, those relating to supply and use phase (maintenance and replacement of components), and finally those of disposal and recycling (held usually by municipal companies, or specific national bodies) must be taken into account.

Durability, frequency of maintenance and/or repair are requirements that must be considered in the evaluation of circularity requirements, as they allow to obtain indications on the effectiveness of use of the product. Difficulties arise for the comparison of different kind of indicators, namely physical indicators (amount of materials used and waste generated) or usage indicators (e.g. load factor, decay curves).

One solution to the problem is the adoption of specific KPIs (Key Performance Indicators), which address all the five elements of the CE (both physical and usage factors) to arrive at a single, non-ambiguous result. For each phase of the product life cycle, in addition to the data regarding the use of resources and the methods of use, also the economic data must be taken into account to evaluate the overall cost-effectiveness of the process.

The choice of the best solution to pursue can only be identified through a careful and in-depth assessment of market scenarios through environmental and economic assessments where it is possible to identify all the possible implications of the system and all the consequent changes that should be applied to improve the sustainability of the system. The economic component, alongside the physical one, allows to obtain an overall picture in terms of circularity and therefore to concretely evaluate, for example, if the choice to use certain resources guarantees greater durability to the product.

The measurement of circularity is an approach that should run jointly and alongside other environmental impact assessment tools for products and/or services, such as the Life Cycle Assessment or the Carbon Footprint. The measurement of circularity is an essential requirement to pursue CE principles and guarantee greater transparency for the market and the consumer. The following consequences can arise from the diffusion of sustainability measurements:

- taxation and public incentive actions can turn to instruments of "reward" with reference to the results obtained with sustainability measurements. Such policies will make up a driving force that, on the one hand, recognizes the achievement of a result for the company and, on the other, pushes towards sustainable market demand.

- The consumer, one of the main actors of the market economy, must be actively involved, and adequately informed, in pursuing responsible and sustainable actions when purchasing a product. In order to achieve this, the consumer himself should be able to understand and evaluate how much a products complies with "circularity" requirements.

3 Legislative framework

The present Chapter discusses the legislative context, with a focus on the European and Italian legislation, regarding two key points:

- The current legislation on the application of sustainability criteria to the public bidding process as a mean to promote the purchase of more sustainable products by the PA;
- The current international standards regulating the information management and the use of Building Information tools, as well as the local Italian legislation regarding the progressive mandatory introduction of BIM tools in public projects.

3.1 Minimum Environmental Criteria (MEC)

The Minimum Environmental Criteria (MEC) are the environmental requirements that allow the identification of the design solution, the product or the best service from an environmental point of view throughout the entire life cycle, are defined within the framework of the Plan for environmental sustainability of consumption in the public administration sector and adopted by Decree of the Minister of the Environment for the Protection of the Territory and the Sea (Interministerial Decree of 11 April 2008 and confirmed with the Decree of 10 April 2013). The Plan aims to increase the dissemination of "Green Public Procurement", or Green Purchases, or, according to what established by the European Union, the process through which Public Administrations purchase goods and services having less impact on the environment during their life cycle. Thanks to the promotion and use of GPP, public authorities they can influence the market by stimulating the industry to develop green technologies that cover the entire cycle of life of the products: from production to supply, up to transport, use, and disposal.

The obligation of GPP was introduced for the first time by art. 68 bis in Legislative Decree n. 163/2006 s.m.i.. The PA, in order to make sustainable and green purchases, must comply with the indications provided for the MEC annually indicated by the Ministry of the Environment in special lists that identify the categories of goods and services, the environmental impacts and the volumes of spending.
The national legislation governs the MEC and their effectiveness under Article 18 of Law 221/2015e, of the art. 34 bearing "Energy and environmental sustainability criteria" provided for by Legislative Decree 50/2016 "Procurement Code" (amended by Legislative Decree 56/2017), which required it to be mandatory for all contracting stations.

The obligation ensures that the national policy on green public procurement is incisive not only in the objective of reducing environmental impacts, but in the objective of promoting more sustainable, "circular" production and consumption models and in spreading employment "Green", at the same time rationalizing consumption and spending review.

MECs are divided into 17 categories of supplies and assignments, in addition to the minimum environmental criteria for the assignment of design services and works for the new construction, renovation and maintenance of public buildings, which govern the selection of candidates, the technical specifications for buildings or groups of buildings, from the technical specifications of the construction site to those of the building components up to the award criteria and the conditions of execution.

The MEC documents, each in its specificity, have a similar basic structure.

In the Introduction, the environmental and social legislation of reference, suggestions proposed to the contracting authorities for the analysis of needs, further indications relating to the completion of the related tender and, where the definition of a document of technical support, the approach followed for the definition of the MEC.

The Object of the contract highlights environmental sustainability and, where present, social sustainability, in order to indicate the presence of environmental and possibly social requirements in the tender procedure. The contracting authorities should always indicate in the subject of the contract the ministerial decree approving the environmental criteria used.

The actual Minimum Environmental Criteria are defined for some or all of the stages of definition of the tender procedure in particular for:

- Selection of candidates: these are subjective qualification requirements designed to prove the candidate's technical ability to perform the contract in order to cause the least possible damage to the environment
- Technical specifications: as defined by art. 68 of Legislative Decree. 50/2016, "define the characteristics envisaged for works, services or supplies. These characteristics may also refer to the specific process or method of production or performance of the works, supplies or services requested, or to a specific process for another phase of their life cycle even if these factors are not part of their substantial content, provided that they are linked to the subject of the contract and proportionate to its value and objectives ".
- Reward criteria: that is, requirements aimed at selecting products / services with better environmental performance than those guaranteed by the technical specifications, to which to assign a technical score for the purpose of awarding according to the offer at the best value for money.
- Contractual clauses: provide information to execute the assignment or supply in the best way from an environmental point of view.

Each environmental criterion also reports, in the Verifications section, the means of proof to demonstrate compliance.

The environmental criteria are identified starting from a market analysis of the sector concerned and drawing on a wide range of requirements, including those proposed by the European Commission in the European GPP toolkit ("toolbox") or among those indicated by the regulations that impose certain environmental standards.

With specifical reference to road pavement construction and maintenance, a specific group of EU GPP criteria was developed for the product group "Road Design, Construction and Maintenance" [18]. The actual application of such principles is supported, like in other public bidding areas, by a draft Guidance document and a Technical Report that provide insights on how to integrate GPP criteria into the public procurement process, as well as providing further details on the reasons for selecting sustainability criteria.

Considering decreasing level methodological and technical complexity, the award criteria in the public bidding process available to procurers are as follows:

- Life Cycle Assessment (LCA): The carrying out of a Life Cycle Assessment. This requires bidders to collect inventories of input and output flows from the system under analysis and evaluate the life cycle impacts of the main road elements.
- Carbon footprint (CF): The carrying out of a Carbon footprint. This requires bidders to evaluate the life cycle Global Warming Potential of the main road elements.
- Requiring recycled and reused content: This requires bidders to provide materials with a minimum requirement as regards the amount of recycled and reused content for the main road elements.
- Requiring certain useful life thresholds. This requires bidders to provide solutions with a minimum performance requirement in relation to the predicted number of years before certain structural distresses occur on the road pavement.
- Requiring reduced emissions from transport phases: This rewards low CO_{2eq} emissions from the transportation of the aggregates, binders, finished products and waste used for the main road elements.

3.2 Environmental Product Declarations

Intended as a metric of the environmental sustainability of a product system, Life cycle assessment (LCA) methodologies were originally developed to create decision support tools for distinguishing between products, product systems, or services on environmental grounds. During the evolution of the methodology, a number of related applications emerged, including its use as basis to communicate the overall environmental performance of the products to stakeholders [19].

Internationally, LCA-based environmental labels can be used to express the environmental performance of products or services. The International Standards Organization (ISO) has classified the existing environmental labels into three typologies—types I, II, and III—and has specified the preferential principles and procedures for each one of them [20-23]. An Environmental Product Declaration (EPD), also referred to as type III environmental declaration, is a standardized [22] and LCA-based tool to communicate the environmental performance of a product [24]. Several rigid methodological requirements must be carefully carried out to set the basis for a LCA-based EPD. They concern detailed specifications on how to model the product system in the LCA, what to include, what data to use, which environmental indicators to report, etc. All these requirements encompass different product groups in the industry and are known as product category rules (PCRs). The full application of PCRs would allow to make comparisons between different producers of the same products according to common rules. And as such, LCA would benefit from the PCRs in terms of clearness and transparency in the communication of results towards external subjects.

In 2002, to stimulate demand for greener products through easily accessible, understandable, and credible information, Directorate-General for Environment, the European Commission department responsible for EU policy on the environment, commissioned a study on the subject of EPD [25], with the aim to document and evaluate national and sectoral EPD schemes as well as compare them with each other and with the current state of standardization work at ISO level. In 2012, 10 years after the first report, DG Environment published the draft of a harmonized methodology for the calculation of the environmental footprint of products (including carbon) [26]. Nowadays, EPD is even more a tool to communicate credible information about the environmental performance of products, and program harmonization is still a key issue to be managed to broaden its application. In fact, the growing number of different EPD schemes with different requirements can lead to trade barriers on that market, which could be avoided by the development of general guidelines regarding scheme management and the application of LCA and through the mutual recognition among the different schemes. The guide published by the European Commission moves in this direction.

3.3 Building Information Modelling: definition and international standards

The full digitisation of construction projects can be addressed as a reality nowadays, allowing all participants to a project to improve the productivity and efficiency in their work. The designation for what can be referred to, in a simplistic way, as the digitalization of all project-related data is Building Information Modelling (BIM). Initially developed to assist the architectural field, BIM has caught the attention of the infrastructure engineers and has been adopted with success worldwide. The origins of the BIM as a concept can be reported back to the 1970s; Charles M. Eastman [27] specifically suggested the coupling between a quantity and geometric analysis with its complete description, as well as the automatization of data preparation (including cost estimation and material quantities). The first appearance of the term “BIM” is assigned to the article by Nederveen and Tolman entitled “Modelling multiple views on buildings” [28].

Several countries began, in the last decades, to create laws demanding the implementation of the digitisation of public projects. The Scandinavian countries are amongst the first ones to require BIM technologies and methodologies to be used in construction projects. In Denmark, BIM has been mandatory since 2007 for all public projects, in Norway since 2016. In Sweden, the government is establishing plans to mandate BIM as the public Transportation Association started to require the adoption of BIM in 2015. The United Kingdom is a leader when it comes to BIM adoption, in 2016 BIM level 2 (where collaborative work practices are central) was made mandatory for public projects [29].

Some countries opted for a gradual introduction of BIM, based on the project's value. One such introduction is taking place in Italy where, with the Ministerial Decree 560 of 2017, the timeline for the mandatory but gradual introduction of the use of digital modelling methods and tools for the Construction Sector based on the asset's tender value is set. From January 2019, public works with a tender value starting from 100 million euros are compelled to use approaches as Building Information Modelling (BIM), in 2025 this will be extended to all public works [30].

BIM supports innovative workflows applied to built projects, accompanies them throughout their lifecycle, including design, construction and operation phases, offering the possibility to access and oversee all related information (Figure 1). The International Organization for Standardization (ISO) provides the definition of asset as "item, thing or entity that has potential or actual value to an organization" [31], clarifying also that they can be divided in physical and non-physical (e.g. digital assets, licences, intellectual property rights). In the PAS 1192-5:2015 (Specification for security-minded building information modelling, digital built environments and smart asset management) [32], a built asset is defined as a building or infrastructure subject to a construction project or where the related information is held digitally.

Borrmann et al. [33] defines BIM as comprising the "methods and tools for the continuous digital support of the planning, construction and operation phases of the lifecycle of built facility based on a digital building model.", highlighting the continuous support provided throughout all project phases and replacing "building" for "built facility", encompassing also infrastructure assets.

Therefore, the operation phase is the one that benefits most from the proper adoption of BIM, where maintenance and management efficiency is enhanced and more consistent, when properly supported by updated, easily accessed and reliable data. Roads, highways and airport runways are clear examples of linear infrastructures for which the operation phase, namely the time span that goes from construction to end-of-life phase, is extremely interconnected to the pavement condition; pavement asset projects should therefore include the drafting of a Pavement Management System (PMS) [30].

The ISO 19650 [34,35] sets up the main standards for information management processes using BIM. Building information modelling (BIM) plays a key role in information management because it provides the actors of the management process with a methodology that helps structuring information so that the relative technology can be able to process it. Structuring the information content of a digital model using industry standards can help to improve interoperability and transparency in the information exchange. Digital technologies can then enhance the extraction of additional valuable knowledge from it. In this context, it is clear why structuring the information in a certain way can enhance consistency, repetition and predictability.

Among the internationally recognized BIM compartments, the project information models (PIM) support the delivery of the project and contribute to the Asset information models (AIM) to support asset management activities. AIM and PIM are, on the one hand, the structured repositories of information and, on the other hand, useful analytical tools for making decisions during the whole life cycle of a built environment asset, which includes the design and construction of new assets and the operation and maintenance of existing assets. It is expected that, moving forward through project delivery and asset management, the amount and detail of information stored in information models, and the different purposes it will be used for, will surely increase. The information stored into AIM and PIM can be regarded as structured and unstructured information: the first one involves geometry, schedules and databases, while the second mostly refers to documentation, video and sound recordings.

As stated in ISO Standards, information management can be represented as a sequence of maturity stages, shown as Stages 1, 2 and 3 in Figure 1. The Figure shows that the ultimate goal of leveraging BIM to increase business benefits strictly depends on the development of new standards, as well as the combination of advances in technology and more sophisticated forms of information management. Stage 2 maturity is also identified as “BIM according to the ISO 19650 series”, and refers to a stage in which the information management processes used to generate the complete information model can be either manual or automated. The information model includes all information containers, each one specifically delivered by task teams in relation to an asset or a project.

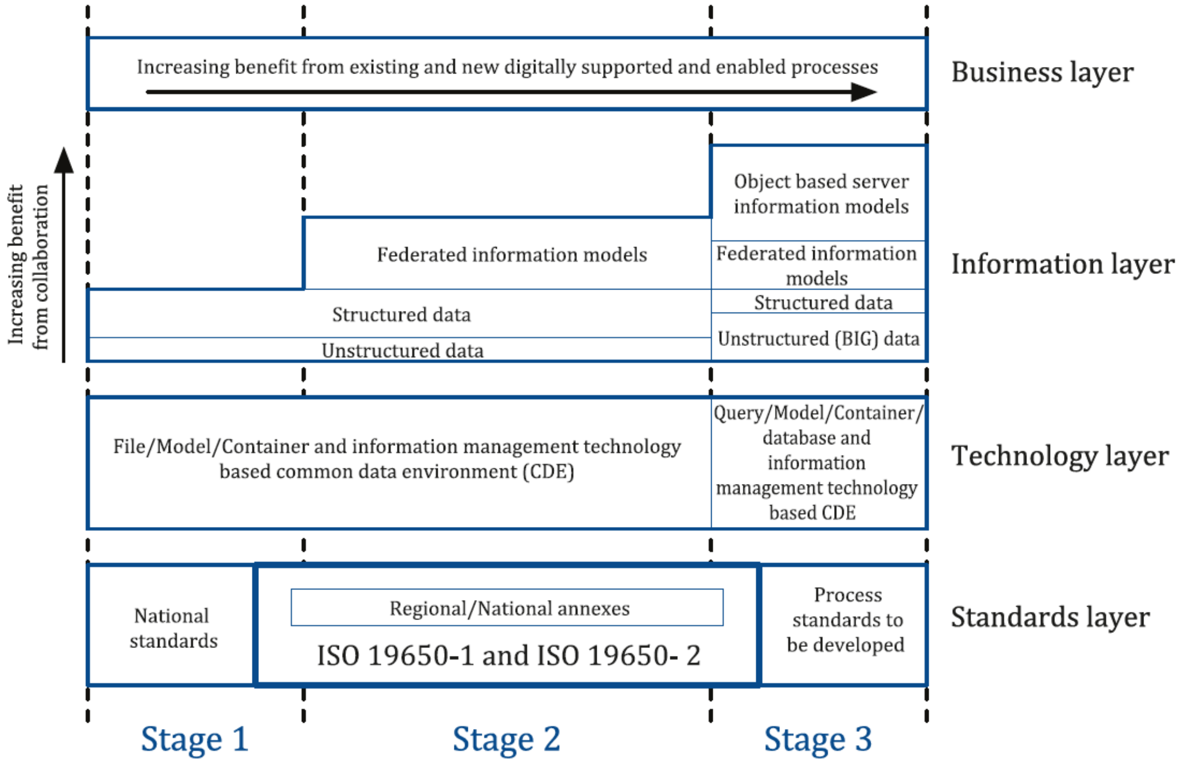


Figure 1 - A perspective on stages of maturity of analogic and digital information management [34]

The PIM is also regarded as a tool to provide a long-term archive of the project, that can help storing information and make them available for auditing purposes. Moving forward from plain geometrical data, the PIM can contain more advanced details such as the location of equipment, the construction technologies, the cost details of each component and the performance and maintenance requirements, during project design, construction and operation.

The specification and delivery of project and asset information follows several principles, of which the main ones are listed below:

1. An asset management system requires the capability of the system to support decision-making at all stages of the life cycle of the asset itself; examples of decisions that require proper information management include the development of new assets, the modification/performance improvement of existing assets and their decommissioning/demolition.

2. On the one hand, the appointing party is the responsible entity for defining the sets of requirements that the information should have; on the other hand, the delivery teams progressively deal with the planning and execution of information delivery.

3. The Common Data Environment (CDE) regulates the information exchange through sharing and coordination of information using, whenever possible, open standards and clearly-defined operating procedures to enable a consistent approach by all organizations involved in the project.

AIM and PIM are produced and updated throughout the information life cycle to provide information models specifically targeted at making asset-related and project-related decisions.

As already mentioned, all asset and project information that is to be supplied during the asset life cycle is strictly linked to the sets of information requirements specified by the appointing party. The relevant information requirements should be issued as part of the procurement process. This also applies when work instructions are issued by one part of an organization to another part of the same organization. The lead appointed party and the appointing party should respectively prepare and review the response to each specified requirement; the response is then managed and further developed by each lead appointed party and finally included in the specific plan for their asset management or project delivery activities; the final stage consists of the acceptance or rejection of the delivered information by the party specifying the requirements. Feedback loops provide for information deliverables to be revised, if necessary. The generic flowchart for this process (ISO 19650) is shown in Figure 2.

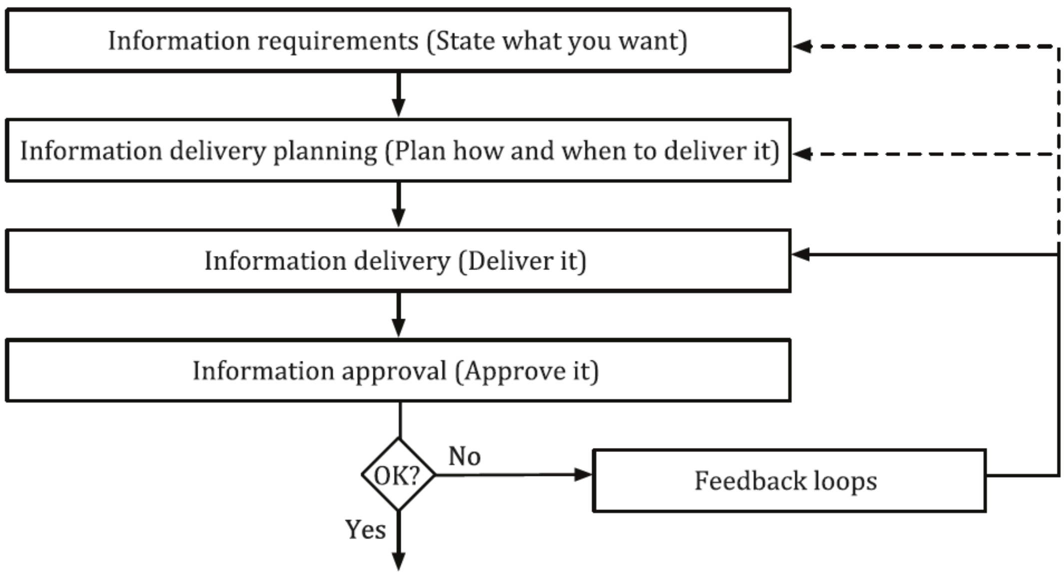


Figure 2 - Generic specification and planning for information delivery

The amount and the degree of complexity of project information highly affects project information management processes. Project information management involves leadership in establishing the project's information standard, the production methods and procedures, and the project's CDE.

In order to allow collaborative working to be achieved in a BIM process, the fundamental principles of must be defined as follows:

a) the information produced by the authors, which is subjected to intellectual property agreements, can be controlled and checked, only sourcing approved information from others where required by direct information exchange;

b) the information requirements must be clearly defined, at high level, by interested parties associated with the project or asset and, at detailed level, by the appointing party;

c) the proposed approaches, capabilities and capacity of each delivery team must be considered and evaluated by an appointing party prior to any appointment;

d) a CDE must be provided to manage and store the shared information in an appropriate and secure way for all individuals or parties who are required to produce, use and maintain that information;

e) the information models must be developed through technologies that are compliant and conform to ISO 19650 Standards;

f) security of information must be ensured during the whole life time of the asset to avoid unauthorized access, information loss or corruption, degradation and, eventually, obsolescence.

A CDE workflow should be implemented to allow information to be accessed by those who require it to undertake their specific function in the BIM process. The CDE solution and workflow enable the development of a federated information model, which includes information models developed by the lead appointed parties, the delivery or task teams. Security and information quality should be considered and, where appropriate, integrated into the definition of or the proposals for the CDE. Issues in the information model should be appropriately identified before the delivery of information. Examples of issues that should be identified are spatial/time issues, e.g. compenetrating structural elements and building services both from a spatial and temporal point of view, or functional issues, e.g. specific features of materials may be incompatible with the required performance of a building element.

The concept of level of information need (LOIN) of each information deliverable should be determined according to its purpose, including an appropriate determination of quality, quantity and granularity of information. The concept of LOIN is strictly linked to the amount of information that is needed to answer each relevant issue across the project. Anything beyond this minimum is considered as waste.

Information management and information production/delivery are closely related concepts; the information that is required to be made available or transferred between operational phase and delivery phase activities is specifically referred to the share of relevant information. That is why information management should be applied during the whole life cycle of the asset, considering that the quantity of information being managed generally increases both during the delivery phase and during the operational phase.

The information management process can be applied to trigger events that are foreseen and scheduled in advance, as well as to trigger events that have not been scheduled in advance: the difference between the two cases is in terms of when the preparatory activities of identifying and appointing the lead appointed party take place.

Some examples of scheduled trigger events are the annual maintenance tasks, for which it is possible to select and appoint the lead appointed party well before any of these trigger events takes place.

The unscheduled trigger events, instead, can foresee two different scenarios: a) the first is the deliberate decision to begin a new project, b) the second scenario refers to rare and unpredictable trigger events (i.e. breaking of equipment or accidents) that having appointments in place can be inappropriate or not possible. In this case, the appointment of the lead appointed party occurs right after the trigger event takes place.

In this context, the implementation of analytic tools to automate such tasks is an important development to fully apply BIM potentialities. The automation of certain design/calculation tasks often leverages the concept of “Computational Design”, which refers to the ability to link creative problem solving with powerful and novel computational algorithms to define new design solutions, leveraging the computational capabilities to customize processes and propose innovative way of managing an asset. Computation might be leveraged for a variety of tasks such as automating certain tasks, run simulations and analyses.

Regardless of the end-use, what is clear from the outlined context is that designers need new frameworks that let them construct their own tools.

4 Literature review

The present Chapter illustrates a literature review of the main fields of research relating to

- The application of life-cycle based methodologies to road asphalt pavement systems, particularly relating to the production, construction, maintenance and rehabilitation strategies;
- The traditional and innovative approaches to pavement management, including distress detection and damage prediction;
- Some applications related to the development of pavement BIM projects and early stage definition of more advanced information models aimed at the integration of damage prediction and assessment.

4.1 Life Cycle Analyses in road infrastructure projects

In the context of enhancing the sustainability of road infrastructure projects, the life cycle thinking approach is often addressed as an effective methodology to quantify sustainability indicators with a view to the whole life cycle, from conception and design throughout operation and final dismission, supporting comprehensive decision-making processes that involve environmental, economic and social indicators [36, 37].

Some of these techniques are well consolidated in the construction industry, and especially in the field of road asphalt pavement management, i.e. Life Cycle Cost Analysis (LCCA); others instead, like Life Cycle Assessment (LCA) for the assessment of the environmental impacts of the life cycle of a system, have a well-consolidated framework but are still on the way to be properly integrated into pavement maintenance management. Lastly, Social Life Cycle Assessment (S-LCA) methods, although standardized by the same methodological framework as LCA, have not yet reached complete acceptance from the scientific community, still presenting many challenges in its implementation and in the definition of impact pathways [38]. For this reason, S-LCA will not be included in the development of the present pavement management framework.

In particular, aiming to reduce the consumption of non-renewable raw materials and fossil fuels, researchers are investigating, through internationally-consolidated and standardized LCA methodology, the potential environmental burdens and the relative benefits of alternative bituminous materials containing secondary raw materials in substitution of natural ones [39, 40], considering bitumen modification to extend their service life [41], or produced through warm or cold technologies, where bitumen emulsion or foamed bitumen is adopted instead of plain bitumen to enhance the compactability, workability and construction quality of asphalt mixtures at low temperature [42, 43]. Additionally, comparative LCAs [44] have been applied to different construction and maintenance solutions that entail the use of sustainable asphalt mixtures and compare the results with those obtained for traditional materials made up of natural aggregates and bitumen and mixed at high temperature (170°C-180°C) for designing and maintaining asphalt pavements.

A significant issue when applying LCA to support decision-making in the field of road pavement management is that it often requires large time expenditure and data; therefore, it is often performed at the end of the design phase, when most of the project features (i.e. geometry, materials) have been already defined, leaving no time to incorporate environmental aspects into decision-making [45].

A much more consolidated practice can be observed when it comes to LCCA of road pavements and its integration in pavement decision-making and maintenance management.

LCCA is a well-consolidated analytical methodology that leverages economic principles to assess the long-term economic sustainability of a project and provide alternative investment options for the decision-makers; in the field of infrastructure management processes, it is regarded as a robust tool to select optimum strategies according to the resources available to the managing bodies. By comparing the resulting Life Cycle Costing (LCC) indicator of two or more alternatives, an optimal investment alternative can be found that should minimize the total long-term cost by finding a suitable trade-off between spending today and lowering the future entity and frequency of maintenance interventions that entails future savings [46]. Indeed, the life cycle perspective of LCA refers to the evaluation of all future costs related to design, production, construction, operation, maintenance and end-of-life stage (reusing/recycling/disposing); that means every phase in the system life cycle [47].

Despite LCC techniques have been traditionally used to manage road pavement assets, during the last decade many US departments of transportation (DOTs) and researchers dedicated considerable efforts to answer four main key issues:

- the evolution of LCCA methodologies [48-50] and automation through computer tools [2];
- the implementation of practical guides to efficiently apply LCCA concepts and handle the consequent results [51, 52];
- the documentation of past experiences of US DOTs in LCCA application [53, 54];
- the development of LCCA-based comparative assessments of alternative road pavement materials, pavement design configurations, construction technologies and M&R alternatives [55, 56].

Such sustainable practices benefit, on the one hand, from newly-developed materials, eventually including high content of recycled materials in their mix design, for constructing new pavement structures and, on the other hand, from the implementation of innovative in-place pavement recycling techniques to rehabilitate existing distressed pavements [57,58]. However, a solution which is found to be environmentally advantageous might not be preferred over another if it is not economically competitive, even if both the alternatives are technically equivalent. Although rehabilitation using in-place recycling is commonly presented as advantageous from an economic point of view, there are still some questions about the extent to which such techniques are cost effective throughout their life cycle. It is also important to quantify which factors are the key drivers of economic performance, and which stakeholders benefit the most with the application of in-place pavement recycling.

4.2 Road maintenance planning

Several studies have been carried out to analyse the benefits of setting up proper maintenance planning; for example, the study carried out by Tavakoli et al [59] shows that, without using an effective maintenance program, a city may see the cost of maintaining their transportation system increase in the future to four or five times what it would cost if the proper maintenance were done before.

The proper scheduling of maintenance treatments is a complex procedure that hides numerous problems that are not easy to solve. For example, some key issue can be identified in the high number of roads to manage, the different cause-effect relations and boundary conditions that link external actions (i.e. load and climate) with the pavement functional and structural state, deterioration rate and consequent distresses.

Picado-Santos at al. [60] developed a maintenance algorithm based on a single condition indicator and several imposed constraints on costs, number of interventions, intervention priorities and more; they estimated the costs involved in the development of the overall system and having the system up and running, including the hardware needed, equal to less than one cent per square meter of the total road network–which is about 150 times less than the cost of a simple surface treatment. It is clearly profitable to have an effective tool to aid decisions about financial resources allocation to maintenance actions in any road network.

Furthermore, the preventive preparation of a maintenance plan makes it possible to reuse waste, such as the milled asphalt material, in order to provide eco sustainable solutions and lower the total costs of road network maintenance [61, 62].

As stated by Koch et al. [63], the process of pavement condition assessment is divided into three parts: data collection, distress identification and classification, and distress assessment.

In order to improve the efficiency of distress detection and the consequent scheduling of maintenance interventions, several researchers have been focusing on implementing more and more automated monitoring techniques.

For example, Jang et al [64] installed into a car a triaxial accelerometer, GPS sensor, microcomputer and local memory for monitoring data collection; this allowed to continuously gather detailed surveys of the status of the network in a short time at low cost.

Kamaliardakani et at [65] automated the survey of cracks on the pavement surface by implementing an algorithm for the identification of cracks that exceed a certain threshold using 2D images obtained through photographic surveys.

Looking at the evaluation of the performance of automated survey techniques, the issue of computational time has been analyzed by Jiang and Tsai [66], who proposed a monitoring system based on a high-resolution 3D laser imaging system. In 3D pavement however, with high data resolution, the computation time of a dynamic optimization algorithm increased exponentially, showing limited possibility of implementation and low performance in real applications.

Instead, to date, the pavement condition assessment and relative decision-making is predominantly performed manually, or still requires a consistent share of manual intervention, and does not yet find a full implementation in automated contexts.

4.3 BIM adoption and infrastructures

In recent years BIM tools began to spread across engineers to efficiently archive, store, manage and analyse large amounts of data generated by different actors and analytic tools involved in the project, supporting decision making in road asphalt pavement design and management [67, 68].

Delgado et al. [69] analysed the possibility of inserting monitoring data into a BIM, obtaining the practical advantage to evaluate design/management alternatives already in the design phase. Indeed, applying modifications to a BIM, i.e. reinforcements, maintenance actions, alterations to the original structure, or changes in survey methods, generates instant changes and easily readable updates for the users.

Looking more specifically at pavement structural and performance data, BIM has been leveraged to provide some embryonal analytics; Tang et al. [9] developed the digital model of a road pavement and coded a customized script aimed to perform structural controls and check the accumulated rutting damage at the end of the predicted service life basing on empirical models fed by asphalt mixture-specific data regarding its physical and the mechanical properties.

In recent years, the need to include sustainability indicators and apply the life cycle approach to the design and maintenance of road infrastructures has further promoted the use of BIM-based tools, moving forward from just geometrical detail, 3D visualization [70-71] and interference detection [72] to the integration of more advanced information and analytics in the BIM process to actively support design and management tasks [9]. So, in its most developed form, BIM should be observed as a digital and smart representation of data-enriched objects created through the collaboration between the involved parties to provide feedback at the earliest possible time, improving decision-making processes, and prompt project efficiency at all stages of the life cycle [73]. For this reason, BIM can be regarded as a key tool to help designers in the storage, analysis, and generation of relevant information related to the life cycle environmental sustainability of a project.

In the infrastructure sector, few efforts have been dedicated to the full integration of BIM potentialities with life cycle based methodologies to assess the environmental and cost sustainability of a project.

Among others, Liu et al. [74] proposed a theoretical framework for introducing a sustainability infrastructure rating system in a BIM environment that helps establish the consistency of each element’s attributes (both functional and physical) in relation to a set of sustainability thresholds. Antón and Díaz [75] introduced two methodologies for the integration of BIM and LCA. The first approach relies on the extraction of information from the BIM model to assess LCA impact categories; the main advantage is the accuracy of the results, while a drawback is the increasing complexity of the BIM model. The second approach is mostly based on manual input of the environmental performance indicators in the pavement information model, which does not require any programming skills or efforts but totally lacks dynamism of the information and analytic capabilities.

Looking at how researchers leveraged the information exchange to implement basic environmental sustainability assessments in the BIM environment, Kaewunruen et al. [76] enriched the information model of a bridge project with the embodied carbon footprint of the lifecycle of different elements, basing on their constituent material identifiers and obtaining a metric of the environmental impacts of each model component that was later manually transferred from the BIM environment to the LCA tool. Lastly, Slobodchikov at al. [77] developed an Autodesk Civil3D application that focuses on the calculation of a specific impact category indicator, namely the Global Warming Potential (GWP), of a road asphalt pavement structure basing on the material volumes of each layer and the construction operations scheduling gathered from the information model, also returning a visual representation in a colour scale of the GWP of each element of the road pavement.

5 Research gaps and objective

Although BIM tools are offering increasing possibilities to customize projects with detailed analysis tools to integrate sustainability criteria already in the design stage (e.g. selection of materials, prediction of structural performance, visualization of environmental impact indicators, cost minimization), a comprehensive effort has not been dedicated yet to the depiction of a life-cycle based sustainability framework specifically designed for BIM-based road pavement projects.

In detail, the following points have been identified as the main gaps that should be filled to prompt the interest towards BIM-based sustainability management of road pavement projects:

- The definition of a pavement information model oriented to sustainability-based pavement management;
- The development of multiple analysis tools to automate life-cycle based calculations using data fed by external sources and allowing bidirectional exchange of information with the informative content of the BIM;
- The integration of decision-making frameworks into road pavement BIMs to improve the capability of engineers to take more sustainable actions and maintenance planning already at the design stage.

This research work aims to integrate BIM tools with road pavement management systems aimed at supporting the definition of maintenance strategies that maximize structural performance and economic and environmental sustainability of the life cycle.

The methodology integrates the traditional structure of road maintenance management systems with a more thorough use of tools for predicting the decay of performance with time, based both on the visual and instrumental survey of the conditions of the pavement in situ, and on the use of synthetic status indicators, such as the Pavement Condition Index, and empirical laws of accumulation of fatigue and rutting damage.

The evaluation of alternative maintenance strategies takes place according to a life cycle approach, in accordance with the methodologies of Life Cycle Assessment [24], and Life Cycle Cost Analysis [78], aimed at the use of innovative practices and technologies to preserve the characteristics of materials over time, containing costs and reducing impacts on nature, resource consumption and pollutant emissions over the useful life of the superstructure.

The alternative strategies, defined by a set of parameters that express the minimum level of service, the residual useful life at the end of the analysis period, the discounted costs of the life cycle incurred by the managing body and the multiple categories of environmental impact indicators, are screened through multi-criteria analysis methodologies for the assignment of a utility score to define the priority of each maintenance intervention [79].

The main aspects addressed in the present research concern the following points:

- Definition of a decision support system oriented to predictive maintenance, which considers the variables related to economic and financial aspects, up to the environmental and technical-operational ones, relating to the decay of specific status indicators, which is formulated to automate the drafting of a multi-year maintenance plan.
- Digitalization of the road pavement management process through the drafting of digital maintenance plans in the BIM environment. Integration is intended not only as the automation of data management, but also as the definition of specific information exchange management protocols relating to the life cycle of a road pavement.

The main practical-applicative feedback consists in the creation of a BIM-plugin, in support of the designers and the road management bodies themselves, which interacts with the informative content (geometric, functional, structural, cost and environmental-related parameters) of an I-BIM model, supported by continuous and updated flows of data relating to the monitoring of the pavement in situ, to provide instant, automated and continuous prediction of the performance, costs and environmental impacts of the life cycle.

The script is intended as a quick tool to automatically provide a report of several environmental impact category indicators of an asphalt pavement design solution, also allowing the selection of alternative materials and technologies from a default library of unit processes, eventually editable by the users to include project-specific assessments. The obtained information can be also used to support the comparison of traditional and alternative pavement design configurations, other than convey into further BIM-integrated decision-making frameworks.

The creation of a management system specifically designed to dynamically interact with digital objects and their information content represents the necessary innovation to ensure the transition towards the complete digitalization of the world of road construction, paving the way for the increasingly frequent use of sustainable solutions from a technical, economic and environmental point of view.

6 Methodology

The present Chapter discusses the main aspects of the most relevant methodologies applied to make up the life-cycle based management approach implemented into the BIM project of an asphalt pavement. Aiming to deliver a detailed pavement information model, the research involved the design and characterization of asphalt materials, using both hot and cold production technologies, and the subsequent design of asphalt pavement solutions that satisfy some predetermined design criteria.

Once a asphalt pavement is built, one way to predict future pavement conditions and provide a predictive maintenance approach based on historical survey data is carrying out continuous and frequent assessments of pavement conditions; thus, the present Chapter discusses the main features and procedures that regulate visual distress assessment of asphalt pavements.

Afterwards, the main principles of LCA, LCCA and Multi Attribute Decision Making (MADM) have been reported in light of the life-cycle based approach to be implemented in the BIM environment.

6.1 Asphalt pavement design and damage prediction

Around 95% of the world’s roads have flexible pavements [80] which allow a more gradual distribution of the load over the subgrade through their stratified system. In fact, the majority of flexible pavement structures can be said to consist of the superposition of three asphalt layers, i.e. the wearing course, the binder, and the base layer, resting on a granular subbase, which lies on the subgrade. The wearing course is in direct contact with the vehicles and constantly exposed to the meteorological agents; the binder, or intermediate layer, provides a gradual stiffness transition from the wearing course and base layer, while the deepest and thickest layer is the base layer, which is in contact with the subbase layer and provides most of the load distribution and structural performance of the road pavement [81].

Traditionally, an asphalt layer consists of a compacted mixture of limestone and/or basalt natural aggregates, filler, and bitumen produced in a plant at high temperatures reaching approximately 170-180°C. This mixture is called Hot Mix Asphalt (HMA).

Road flexible pavement design is a fundamental step to ensure the compatibility of the materials, pavement geometry and subgrade conditions with the loads expected during the useful life of the pavement. Ultimately, pavement design aims to define the optimum thickness of the pavement layers, given the structural model as an elastic, homogeneous, and isotropic multilayer and several input data, such as the mechanical performance of the materials used for each layer (i.e. constitutive law and Poisson ratio) and the design service life, to prevent excessive extension of fatigue cracking damage and rut depth. [82].

Fatigue cracking is a typical distress mechanism that occurs in flexible pavements; it starts at the bottom of the asphalt base layer and propagates to the surface as one or more interconnected cracks. An excessive extension of the area of the pavement affected by fatigue cracking may lead not only to reduced ease and safety in driving but also to the percolation of hazardous substances from the bonded layers to the soil and underground waters, especially when recycled materials are added to the asphalt mixtures [83].

Beside fatigue cracking, rutting is another typical distress phenomenon that often occurs in asphalt pavements and consists of the accumulation of permanent deformations in the asphalt layers, resulting in a depression of the surface along the wheel path. Hazardous conditions on roads can occur because of rutting. The depressions are known to hold water, which can cause the tires to lose contact with the road surface, decreasing road safety, and possibly cause infiltration to groundwater, especially if combined with cracks on the pavement surface. [84]

6.1.1 Stiffness characterization

Preventing fatigue cracking and rutting during the service life of the pavement is the main goal of designing an asphalt pavement. For this reason, asphalt mixtures should be carefully characterized, especially in terms of stiffness and resistance to the main mechanisms of failure and degradation. Although in common calculation models reference is made to the hypothesis of linear elasticity, the bituminous mixtures exhibit a much more complex behaviour, given by the combination of elastic, viscous and plastic components. The evaluation of the constitutive law of asphalt materials, therefore, to be used for the optimal design of the layers of the pavement, during mix design or even for control purposes, must take place by imposing specific load and temperature conditions that are representative of the service ones and linked to the actual performance on site.

The quantity that links the stresses and strains measured under dynamic conditions is the complex modulus E*.

The complex modulus E* is defined as the ratio between the sinusoidal stress with pulsation ω applied to the material $\sigma(t) = \sigma_0 \sin(\omega t)$ and the sinusoidal strain $\varepsilon(t) = \varepsilon_0 \sin(\omega t - \varphi(\omega, \theta))$ resulting from it (see Figure 3).

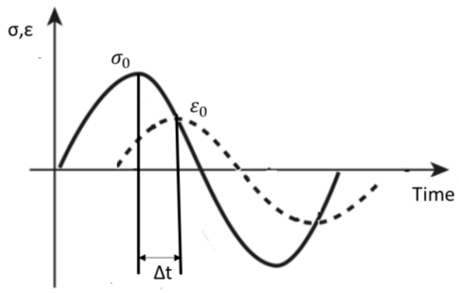


Figure 3 - Stress-strain relation of a bituminous mixture

In complex notation:

$$\sigma(t) = Im(\sigma^*) \qquad \text{with} \quad \sigma^* = \sigma_0 e^{\omega t} \tag{1}$$

$$\varepsilon(t) = Im(\varepsilon^*) \qquad \text{with} \quad \varepsilon^* = \varepsilon_0 e^{i(\omega t - \varphi)} \tag{2}$$

$$E^*(\omega, \vartheta) = \frac{\sigma^*}{\varepsilon^*} = \frac{\sigma_0}{\varepsilon_0} e^{i\varphi} \tag{3}$$

It can be noted that the definition of the complex modulus allows us to extend the laws valid for linear elastic materials to linear viscoelastic materials in the frequency domain.

$$E = \frac{\sigma(t)}{\varepsilon(t)} \tag{4}$$

The norm of the complex modulus also called stiffness modulus is given by Equation (5)

$$|E^*| = \left(\frac{\sigma_0}{\varepsilon_0}\right) \tag{5}$$

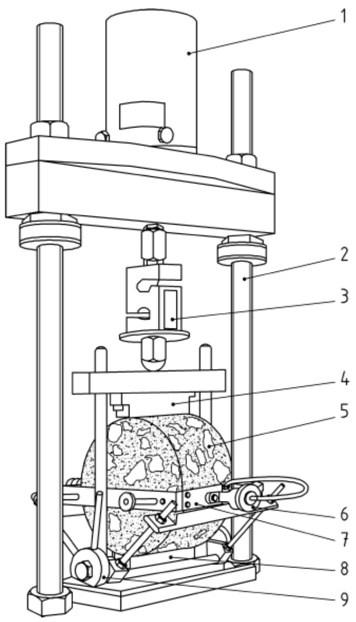
The complex modulus is therefore defined by its norm and its phase angle:

$$E^* = |E^*| \cdot e^{i\varphi} \tag{6}$$

But in the same way also from its real part E_1 and its imaginary part E_2:

$$E^* = E_1 + iE_2 \tag{7}$$

A standardized way to characterize the stiffness of asphalt mixtures in the laboratory is the indirect tensile test as reported in EN 12697-26- Annex C. This method measures the resilient stiffness of bituminous mixtures using an indirect tensile test by applying load with a haversine waveform. The method is applicable to cylindrical specimens of various diameters and thickness, manufactured in the laboratory or cored from a road layer. In Figure 4 shows an example of test equipment.



Key

1 Pneumatic load actuator
2 Steel load frame
3 Load cell
4 Upper loading platen
5 Test specimen
6 LVDT adjuster
7 LVDT mounting frame
8 Lower loading platen
9 LVDT alignment jig

Figure 4 - Stiffness equipment for indirect tensile test by EN 12697-26 – Annex C

The measured stiffness modulus is determined using Equation 8:

$$E = \frac{F \cdot (\nu + 0.27)}{(z \cdot h)} \tag{8}$$

Where:

E is the measured stiffness modulus, MPa

F is the peak value of the applied vertical load, N

z is the amplitude of the horizontal deformation obtained during the load cycle, mm

h is the mean thickness of the specimen, mm

ν is the Poisson’s ratio, equals 0.35

6.2 Monitoring asphalt pavement condition during the service life

During the service life of a pavement, its conditions should be accurately evaluated to identify the severity of pavement damages and types of pavement distress. Therefore, monitoring systems are considered a significant step of maintenance processes.

Evaluation of Pavement conditions which includes evaluation of friction, surface roughness, pavement structure, and existing distresses are considered as one of the main components of pavement design and rehabilitation in any Pavement Management System (PMS). The majority of the cost-effective Maintenance and Rehabilitation (M&R) strategies which were developed using the PMS have resulted in accurate pavement evaluation [85].

Pavement-distress ratings can be subjective or objective. As explained by Bektas, Smadi, and al-Zoubi, “a subjective rating system involves an individual panel of inspectors that drives over the pavement (normally at posted speed) and subjectively rates the pavement sections either using a numeric scale or categorical descriptions such as good, fair, poor, etc., based on observed distress types and ride quality.” [86] A typical document based on which visual assessments of the pavement distresses are made is the Distress Identification Manual for the long-term pavement performance program [87]. Examples of these systems include the PSR and Pavement Surface Evaluation and Rating (PASER) methods [88].

The expansion of the transportation industry and the growth of the strategic importance of road pavement assets has more and more prompted the development of highly efficient monitoring techniques; the development of information and sensing technology has further triggered the invention of advanced monitoring systems for road pavements. Indeed, pavement survey and monitoring is the first step for a proper scheduling of maintenance treatment processes and the overall development of transportation systems [89].

Pavement monitoring traditionally focuses on the detection of pavement surface distresses, like surface texture, distressed patching, potholes, cracks, rutting etc. Many pavement studies focus on the development of new monitoring methods that can provide the best evaluation of pavement condition through synthetic indicators. Also, several researchers have been proposing new competitive and high performance monitoring technologies that are capable of detecting, mapping and analysing pavement distresses with high accuracy, short survey time and posing little traffic disruptions [90].

Due to the lack of financial resources and allocated budgets targeting pavement maintenance and rehabilitation, the evaluation of existing pavement distresses in terms of Pavement Condition Index (PCI) is considered one of the main components of PMS, which is used to identify the deterioration in the pavement sections and identify a proper maintenance strategy.

PCI, a widely used index derived from individual distress-deduct values, was developed in the late 1970s by the U.S. Army Corp of Engineers [91]. It provides a measure of the current condition of the pavement based on the distresses observed on the surface and is intended to be an indicator of a pavement’s structural integrity and surface operational condition (i.e., localized roughness and safety). The type and severity of pavement distress is assessed by visually inspecting pavement sample units. The quantity of distress is measured as described in Shahin et al. [91]; each distress indicator contributes to the overall condition of the sample unit, whose aggregation depends on the homogeneity of pavement condition. The rating scale of PCI indicator ranges from the minimum value, 0, to the maximum value, 100, with 100 representing a pavement in perfect functional and structural condition. The general expression for computing the PCI value is shown in Equation 9 [92].

$$PCI = C - \sum_{i=1}^{p} \sum_{j=1}^{m_i} a\left(T_i, S_j, D_{ij}\right) F(t, q) \tag{9}$$

Where:

PCI is the pavement condition index.

C is the maximum value of the condition index (perfect score, usually 100).

a(T, S, D) is the deduct-value function that varies with distress type (T), severity (S), and density (D).

F(t,q) is the adjustment function that varies with total-deduct value (t) and number of deducts (q).

i and *j* are counters for distress types and severity levels, respectively.

p is the total number of observed distress types.

m_i is the number of severity levels for the i-th distress type (typically, three levels of severity are used: low, medium, and high).

Funding limitations compel to set up proper prioritization of pavement maintenance interventions compatibly with the allocated funds. The prioritization of maintenance strategies is accomplished through the development of systematic procedures for scheduling M&R activities that aim to maximize the anticipated benefits of the road users and, at the same time, reduce the associated M&R cost for the managing agency. Thus, PMS would allow managing bodies and engineers to allocate the required budgets and funds, personnel and resources in an effective manner [93].

6.3 Life cycle assessment principles

The Life Cycle Assessment (LCA) is a method that evaluates the set of interactions that a product or service has with the environment, considering its entire life cycle which includes the pre-production phases (therefore also the extraction and production of materials), production, distribution, use (therefore also reuse and maintenance), recycling and final disposal. Thanks to the impetus deriving from European policies on environment, energy, resources and waste, LCA is increasingly becoming a necessary tool for defining public policies and for the competitiveness of businesses. At the European level, LCA represents, to date, an element of qualification in all fields where an assessment of sustainability is required. It is a methodology that allows to evaluate the ecological advantages of a product, through the quantification of the environmental impacts connected to the production processes and other activities of the company. As for the information provided to the consumer, the

LCA can be of support to increase the truthfulness of the message on the ecological characteristics of a product, which acquires credibility as it is accompanied by numerical data on the impacts.

The LCA procedure is internationally standardized by the EN ISO 14040 and 14044 standards [94, 95]. The LCA (as defined by the ISO 14040 standard) considers the environmental impacts of the case examined on human health, the quality of the ecosystem and the depletion of resources. The objectives of this methodology are to define a complete picture of the interactions with the environment of a product or service, helping to understand the environmental consequences directly or indirectly caused and therefore daring to those who have the decision-making power (who has the task to define the regulations) the information necessary to define the behaviours and environmental effects of an activity and identify opportunities for improvement in order to reach the best solutions to intervene on the reduction of the environmental impact.

The two main regulatory references that represent the main methodological standard for the execution of an LCA analysis applied in a general way, not referred to road works, will be analysed in detail below, since there is still no specific legislation in the national and European context.

6.3.1 EN ISO 14040-14044

The increased awareness of the importance of protecting the environment and the possible impacts associated with the products/services manufactured and consumed has increased interest in the development of methods to better understand and reduce these impacts. One of these techniques under development is LCA. The present Chapter focuses on the internationally-recognized methodological framework of LCA and is entirely based on the guidelines reported by the International Standardization Organization in ISO 14040 through ISO 14044.

The LCA procedure can be applied in numerous industrial fields to support:

- the identification of opportunities to improve the environmental performance of products in the different stages of their life cycle
- information to those who make decisions in industry and in governmental or non-governmental organizations (for example strategic planning, choice of priorities, design or redesign of products or processes)
- the choice of relevant environmental performance indicators with the related measurement techniques

- marketing (for example, the implementation of an ecological label system, an environmental claim or the production of an environmental product declaration).

For LCA professionals, ISO 14044 describes in detail the LCA implementation requirements. LCA deals with environmental aspects and potential environmental impacts throughout the product life cycle, understood as consecutive and interconnected phases of a product system, from the acquisition of raw materials through manufacturing and use, up to the treatment of end of life, recycling and final disposal (i.e. “from cradle to grave”).

The LCA study involves four phases, represented with the related connections in Figure 5.

- Phase 1: the objective and scope definition
- Phase 2: the inventory analysis
- Phase 3: the impact assessment
- Phase 4: the interpretation

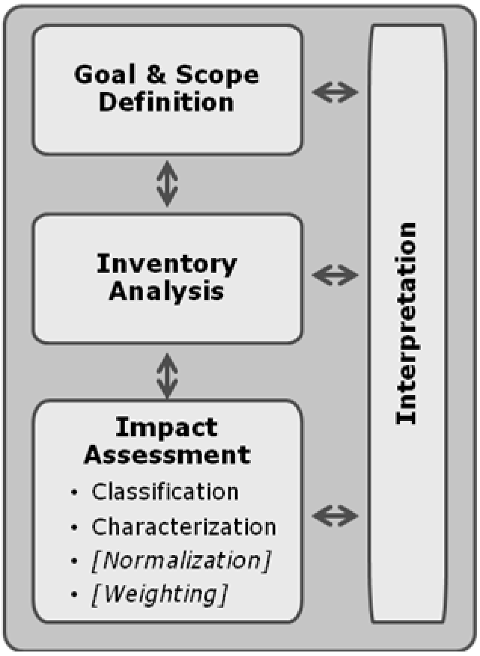


Figure 5 - Stages of the LCA (ISO 14044)

The objective indicates the reasons for the study and the audience to whom the analysis is intended. The field of application, including the limits of the system and the level of detail of the LCA, depends on the subject and the intended use of the study. The depth and breadth of the LCA can differ considerably depending on the objective of a particular LCA. The scope includes the definitions of the product system studied, the functional unit, the system boundary, the allocation procedures, the selected impact categories, the methodologies for assessing the impacts and their interpretation, the quality requirements of the data and assumptions underlying the analysis.

The life cycle inventory analysis phase (LCI phase - "Life Cycle Inventory") is the second phase of the LCA. This is the inventory of incoming and outgoing data relating to the system to be studied. The LCI implies the collection of the data necessary to achieve the objectives of the defined study.

The life cycle impact assessment phase (LCIA phase - "Life Cycle Impacts Assessment") is the third phase of the LCA. The purpose of the LCIA is to provide additional information to help evaluate the LCI results of the product system in order to achieve a better understanding of their environmental significance.

The Life cycle interpretation is the final stage of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed, according to the definition of the goal and scope, as a basis for conclusions, recommendations and decisions.

There are cases in which the objective of the LCA can be met by carrying out a single inventory analysis and interpretation. This is generally known as the LCI study. EN ISO 14040 covers two types of studies: life cycle assessment studies (LCA studies) and life cycle inventory studies (LCI studies).

In general, information obtained through an LCA or LCI study can be used as part of a much more comprehensive decision-making process. Comparing the results of different LCA or LCI studies is only possible if the hypotheses and context of each study are equivalent. Therefore, EN ISO 14040 contains several requirements and recommendations to ensure transparency on these topics.

LCA is one of several existing environmental management techniques (for example: risk assessment, environmental performance assessment, environmental audit and environmental impact assessment) and may not be the most suitable technique to be used in all situations. The LCA generally does not deal with the economic and social aspects of a product, but the life cycle approach and methodologies described in EN ISO 14040 can be applied to these other aspects.

LCA is a relative approach, structured around a functional unit. The functional unit defines what is studied. All subsequent analyses are then related to the functional unit, as all the input and output elements of the LCI and the LCIA profile are related to the functional unit.

As reported by the EN ISO 14040, the basic characteristics of the life cycle assessment methodology are listed below:

- the LCA systematically examines the environmental aspects and the impacts of the product systems, from the acquisition of raw materials to final disposal, in accordance with the defined objective and field of application
- the relative nature of the LCA is due to the functional unit characteristic of the methodology
- the degree of detail and the temporal extension of the LCA are a function of the objective and field of application
- the LCA methodology is open to welcome updates on the state of the art of technology
- there is no single method for conducting LCA. Organizations have the flexibility to practically implement LCA in accordance with EN ISO 14040
- LCA is different from many other techniques (such as environmental performance assessment, environmental impact assessment and risk assessment), however it can use information collected by other techniques
- the LCA does not provide for the assessment of specific or absolute environmental impacts for the following reasons: the environmental impacts are related to a reference unit, there is an intrinsic uncertainty in their modelling and, in most cases, they are expected impacts in future time
- the LCI and LCIA phases provide a perspective on the environmental problems and resources required of one or more product systems
- the LCIA assigns the LCI results to the impact categories. For each category, a life cycle impact category indicator is selected and the result of this indicator is calculated
- the LCIA profile provides information on environmental problems associated with the elements entering and leaving the product system
- there is no scientific basis for reducing LCA results to a single score or number, since weighting requires the choice of values
- Life cycle interpretation requires the use of a systematic process to identify, qualify, verify, evaluate and present conclusions based on the results of the LCA in order to meet the requirements described in the objective and scope of study
- the interpretation of the life cycle also provides for the identification of links between the LCA and other environmental management techniques, underlining the strengths and limitations of the LCA in relation to the definition of its objective and scope.

The object of the LCA is therefore the product system, understood as a system having one or more functions and divided into a series of unitary processes. The unit processes are connected to each other by flows of intermediate products and/or waste to be treated, they are connected with other product systems by product flows and with the environment by elementary flows.

Dividing the product system into unitary component processes makes it easier to identify the elements entering and leaving the product system itself. The level of detail of the modeling that is required to meet the objective of the study determines the boundary of a unitary process. Elementary flows can include the use of resources and releases into the air, water and soil associated with the system. These data are the results of the LCI and constitute the input element for the LCIA.

The system boundary determines the unit processes that must be included in the LCA. It is necessary to establish which unitary processes to include in the study and the level of detail with which these unitary processes are to be studied.

EN ISO 14040 lists the unitary processes that must be included in the system boundary:

- acquisition of raw materials
- main process sequence
- distribution and transport
- production and use of fuels, electricity and heat
- use and maintenance of the product
- disposal of waste and process products;
- recovery of products after use (including energy recovery)
- manufacture of auxiliary materials
- manufacture, maintenance and disposal of main equipment.

The elimination of life cycle stages, processes, incoming or outgoing flows is allowed only if it does not significantly change the overall conclusions of the study and, in any case, must be appropriately justified. In particular, in the practice of LCA, various exclusion criteria are used, listed below according to the definitions of EN ISO 14044:

- mass: all the input elements that cumulatively contribute, in a way greater than a defined percentage, to the mass flow of the product system to be modelled must be included in the study
- energy: all the input elements that cumulatively contribute, in a greater than a defined percentage, to the input energy flow of the product system to be modelled must be included in the study

- environmental relevance: all input elements that contribute more than a quantity defined by the system data collected specifically for their environmental relevance must be included in the study.

The qualitative and quantitative data to be included in the inventory must be collected for each unit process included within the system boundaries. The collected data, whether measured, calculated or estimated, are used to quantify the input and output elements of a unitary process. When data is collected from those published in public sources, reference must be made to the source.

Since the data collection could cover different communication sources and published references, to achieve a uniform and consistent understanding of the product system to be modelled, measures need to be taken, including:

- drawing of non-specific process flow diagrams, which describe all the unitary processes to be included in the model, with their interrelationships
- detailed description of each unitary process with respect to the factors that influence the input and output elements
- list of flows and relevant data for the operating conditions associated with each unitary process
- development of a list specifying the units of measurement used;
- description of the data collection and calculation techniques required for all data.

The macro categories into which data can be classified include:

- incoming energy elements, incoming raw materials, auxiliary materials or other incoming physical entities
- products, co-products and waste
- releases into the air, water and soil
- other environmental aspects.

All calculation procedures must be explicitly documented and assumptions must be clearly indicated and justified; the consistency of the calculation procedures should be maintained throughout all the phases of the study. The incoming and outgoing elements related to combustible materials, for example oil, gas or coal, can be transformed into incoming and outgoing energy streams by multiplying them by the related heat of combustion. In this case it must be recorded whether the highest or lowest calorific value has been used.

The inputs and outputs must be allocated to the different products according to clearly defined procedures, which must be documented and justified together with the allocation procedure. The sum of the elements allocated in input and output of a unit process must be equal to the elements in input and output before the allocation of the unit process.

The allocation process is performed according to the following procedure:

Step 1: Wherever possible, allocation should be avoided by splitting the unit process to be allocated into two or more subprocesses and linking the inbound and outbound data related to those subprocesses, or by expanding the product system to include additional functions relating to co-products.

Step 2: Where the allocation cannot be avoided, the input and output elements of the system should be divided among its different products or functions so that they reflect the underlying physical relationships between them.

Step 3: Where physical relationships alone cannot be established or used as a basis for allocation, the inputs should be allocated between products and functions in a way that reflects the other relationships between them (e.g. in proportion to the economic value of the products).

The allocation procedures must be applied uniformly to the similar input and output elements of the considered system.

For reuse and recycling, additional processing is required for the following reasons:

- reuse and recycling may imply that the incoming and outgoing elements associated with the unitary processes for the extraction and treatment of raw materials and the final disposal of products are shared by more than one system of products
- reuse and recycling can change the properties inherent to the materials
- specific attention should be paid to the recovery processes when defining the system boundary.

Product systems that provide for recycling and reuse operations can be closed-loop, i.e. the material is recycled within the same product system, or open-loop, i.e. the material is intended to be reused in another recycling system products.

Different allocation processes are applicable to reuse and recycling, in particular:

- a closed-loop allocation process is applied to closed-loop product systems. It also applies to open-cycle product systems where there are no changes in the properties inherent to the recycled material. In such cases, the use of secondary material replaces the use of virgin materials
- for open-loop product systems, where the material is recycled into other product systems and the material undergoes a change in its properties, an open-loop allocation process is applied.

Such allocation procedures for divided unit processes should use as a basis for the allocation, if possible, in order: the physical properties, the economic value or the number of subsequent uses of the recycled material.

The LCA phase must be carefully planned to comply with the objective and scope of the LCA study. The LCIA phase must take into account the following sources of uncertainty:

- quality of LCI data as a function of the objective and field of application
- system boundary and data excluded, as the results of the LCI must be sufficient to calculate the results of the indicators for the LCIA
- environmental relevance of the LCIA results, which can be reduced due to the functional unit and the aggregation and allocation procedures.

The LCIA phase therefore includes the collection of the results of the indicators for the different impact categories, which together represent the LCIA profile for the product system.

The LCIA is made up of mandatory and optional elements. The mandatory elements are the following:

- selection of impact categories, category indicators and characterization models
- assignment of LCI results to the selected impact categories (classification)
- calculation of category indicator results (characterization).

When selecting impact categories, category indicators and characterization models in the LCA, reference must be made to the information and related sources. This also applies to the definition of new impact categories, category indicators and characterization models. The selection of impact categories must reflect a complete set of environmental problems related to the product system studied, taking into account the objective and field of application. In addition, for each category indicator, the environmental mechanism and the characterization model that relate it to the results of the LCI must be described.

For each defined impact category, the mandatory elements of the LCIA are:

- the identification of the purpose of the category, or on which environmental aspect the impact category affects
- the definition of the category indicator, understood as a quantifiable chemical phenomenon that causes an environmental impact
- the identification of the appropriate LCI results that can be assigned to the impact category, taking into account the category indicator and the identified purposes;
- the identification of the model and characterization factors.

Furthermore, the purposes of the categories and their environmental relevance must be defined. In addition to these mandatory elements, EN ISO 14044 also includes a series of recommendations, such as the international recognition of the impact categories, category indicators and characterization models used and their technical and scientific validity.

The LCIA classification phase involves the assignment of the LCI results to the impact categories and should take into account the following aspects:

- the direct assignment of the LCI results relating to a single impact category
- identification of the results

After the characterization and before the other optional elements of the LCIA, the elements entering and leaving the product system must be represented by:

- the compilation of the results of the category indicators for the different impact categories, known as the LCIA profile
- inventory results that have not been assigned to impact categories, for example due to low environmental relevance
- data that are not elementary inventory flows.

Some of the optional elements of the LCIA reported by the EN ISO 14044 are the normalization of the category indicators with respect to a reference value, the classification by grouping of the impact categories, the weighting (assignment of weights to the different impact categories and aggregation of the results of the weighted indicators) and the analysis of data quality.

The applications of LCA in the field of environmental management tools include, among others:

- environmental management systems and the assessment of environmental performance such as the identification of the significant environmental aspects of a product
- environmental labels and declarations (ISO 14020, ISO 14021 and ISO 14025)
- the integration of environmental aspects in the design and development of a product (ISO/TR 14062)
- the inclusion of environmental aspects in product standards (ISO Guide 64)
- environmental communication (ISO 14063)

6.4 Life cycle cost analysis

The cost of road construction consists of design expenses, material extraction, construction equipment, maintenance and rehabilitation strategies, and operations over the entire service life.

The American Association of State Highway Officials (AASHO) introduced the concept of life-cycle cost-benefit analysis in its ‘‘Red Book” in 1960. The LCCA was introduced to support highway investment decision-making, and economic evaluation of highway upgrades during the planning stage. The use of LCC concept is supported in the different AASHTO Pavement Design Guide editions [96, 97], which also include detailed discussions regarding costs that should be considered in LCCA.

Looking at LCCA methodology, a key feature is the approach used in the analysis, namely probabilistic or deterministic approach. The deterministic approach is applied when input variables are regarded as discrete fixed variables, (for instance, design life equal to 20 years). However, all the variables fed into any LCCA have a certain level of uncertainty, especially when dealing with predictive models. Uncertainty in the variables governing the phenomenon are usually managed through different methods, such as risk analysis (the probabilistic approach) or sensitivity analysis [98]. In particular, sensitivity analysis allows to evaluate the effect of the uncertainty of the input parameters on model development.

Therefore, the LCCA can help to realistically analyze the economic effectiveness of pavement design, construction and maintenance management alternatives. The economic evaluation of projects is carried out through specific metrics, as follows:

- The internal rate of return (IRR)
- The equivalent uniform annual cost (EUAC)

- The benefit/cost ratio (B/C)
- The Net Present Value (NPV)

In particular, the equivalent uniform annual costs (EUAC) or the Net Present Value (NPV) are the most common indicators used today for infrastructural maintenance planning [99] and allow the comparison of multiple solutions within the same analysis period, considering the cost of each alternative and the maintenance activity timing [46]. The resulting metric, namely the projected value in terms of the present value of money is used for the initial construction costs, the maintenance and rehabilitation costs and the salvage value at the end of the analysis period. The discount rate factor is applied to calculate the time value of money.

Equation (10) can be applied for the estimation of a LCC indicator with the NPV method for a pavement asset from the point of view of the managing body [53, 100].

$$NVP = Construction\ Cost + \sum_{K=1}^{N} Future\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}}\right] \tag{10}$$

Where:
N = number of future costs incurred over the analysis period,
i = discount rate in percent,
n_k = number of years from the initial construction to the Kth expenditure,
n_e = analysis period in years.

The EUAC, instead, converts present and future expenditures into a uniform annual cost, which is the preferred methodology when budgeting is carried out annually. Equation (11) shows the formula for EUAC calculation as a function of the NPV [53]:

$$EUAC = NVP \left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \tag{11}$$

Where:
i = discount rate,
n = years of expenditure

Some specification on the terms of Equations 10 are reported as follows:

- **Initial construction costs:** The initial construction cost is usually presented in the form of unit prices, extracted from previous bid records of similar projects, from local price lists or collected through careful and timely market investigation;

- **Performance period and activity timing:** LCCA outcomes are very much affected by activity timing and performance period, strictly interconnected with the structure of the PMS. Both user and agency costs are impacted. The performance must be recorded at regular intervals from initial construction throughout the operational phase, until reconstruction. Continuous updating and monitoring of pavement condition must be used to forecast the type and magnitude of future maintenance interventions [53].

- **Future costs:** Since the costs tied to maintenance and rehabilitation are to be considered as future costs, M&R operations require careful attention. Preventive maintenance strategies, i.e. light maintenance actions that are performed way before the pavements reaches poor conditions and requires deeper rehabilitation/reconstruction, appear to be much more cost effective compared to conventional maintenance strategies [101]. Indeed, the efficiency of estimation and prediction of future pavement condition, and therefore future maintenance costs, is often affected by the absence of efficient record keeping. Hence, digital tools help in the construction of proper maintenance databases and are required for the application of preventive maintenance concepts [102].

- **Salvage value:** the analysis period, whose definition is crucial to apply life-cycle based techniques, often differs from the service life of a pavement. Beyond the analysis period, a pavements can still be in acceptable conditions and operating. If the assets still have a useful life at the end of the life analysis period, the salvage value or residual value must be determined [52]. Two components make up the salvage value: the first one is the residual value, which refers to the net residual value achievable from pavement recycling [46], while the second one is the residual service life, which corresponds to the pavement remaining life when the analysis period expires. The salvage value can also be set equal as a percentage of the initial pavement construction cost [103].

- **Discount rate:** When long-term public investments are being analyzed, costs are compared at several points of time for which discount is necessary, since money value can change over time. Hence, it is essential to convert the costs and benefits stated at different points of time to the costs and benefits that would happen at a common time [104]. The discount rate is addressed as the the rough difference between the interest rate and the inflation rate and it describes the real value of money across time. The mathematical relationships between interest rate, inflation rate and present-worth cost (PW) are reported in Equations 12 and 13:

$$PW = C \times \left[\frac{(1+i_{inf})}{(1+i_{int})}\right]^n \tag{12}$$

Or:

$$PW = C \times \left[\frac{1}{(1+i_{dis})}\right]^n \tag{13}$$

Where:

PW = present-worth cost,

C = future cost in present-day terms,

i_{inf} = annual inflation rate,

i_{int} = annual interest rate,

n = time until cost C is incurred (years)

i_{dis} = annual discount rate

6.5 Multi attribute decision making

Multiple Attribute Decision Making (MADM) involves "making preference decisions (such as evaluation, prioritization and selection) over the available alternatives that are characterized by multiple and usually conflicting attributes". The problems of MADM can virtually invest any topic [105].

MADM has been a hot research area in management science for a long period of time [106]. An MADM problem is depicted as a decisional problem that involves a predetermined set of alternatives, each one described with a specific set of attributes/indicators. An MADM problem generally requires three methodological steps to be solved:

- determining the weights of the attributes
- normalizing the attribute values for each alternative
- aggregating the normalized attribute values into an overall index to produce the ranking of the alternatives [107].

In MADM problems, weight is commonly defines the relative importance of an attribute within the set of attributes that are available to the decision-maker. Equally weighting the attributes is the simplest way to perform MADM as it requires minimal input from decision-makers. In addition to equal weight, two kinds of methods that can help decision maker to determine the attribute weights can be defined, namely the subjective and objective methods [108]. The subjective method (or subjective weighting method) attempts to use decision-makers judgments to determine the attribute weights. The objective method relies on historical information to define the weight of the attributes: the principal component analysis [109] is one of the widely used objective methods for weight definition.

In MADM problems, the decision-making attributes are usually divided into two types. The first type concerns the qualitative attributes, which are preferred when the values of the indicators can be obtained through specific metrics. However, certain attributes considered in MADM problems cannot be described by quantitative values. Therefore, the second type of decision-making attributes concerns qualitative attributes [110]. Qualitative attributes often rely on qualitative methods (e.g., survey). Also the linguistic data [111] and fuzzy data [110] may be considered to define the qualitative attributes. In addition, the effectiveness of MADM analyses requires the attributes to be independent with each other. If the interdependence among attributes exists, the synthetical values of each attribute should be calculated though fuzzy integrals.

Once the set of alternatives, each one described by pre-defined qualitative and quantitative attributes, has been obtained, each alternative should be comparable to the others; this requires rescaling (or normalization) of the attributes values. After normalization, the value of each attribute will range between 0 and 1, being 1 the highest level of convenience for the decision-maker.

The last methodological step of MADM involves the synthesis of multiple attribute values into a single synthetic value, which automatically defines the ranking or prioritization of the alternatives.

Until now, a number of MADM methods has been proposed by practitioners and researchers; in each specific decision-making problem, the most suitable MADM method should be selected according to the actual features of the case study and the complexity of the explicative variables. If the number of attributes is larger, hierarchical decision models, e.g., analytical hierarchy process (AHP), can be regarded as the most suitable choice. If the number of attributes is smaller, some simple MADM methods may be chosen for use. If the attributes are described by fuzzy numbers, the most suitable methods are fuzzy MADM methods.

Choosing the most appropriate MADM method is a hard task for the decision-maker because different MADM techniques may imply different results when applied to the same problem [106]. Many earlier studies have focused on comparing various MADM methods. The recent study by Zhou and Ang [112] employed the information-loss criterion to compare several well-established MADM methods in constructing composite indicators for performance assessment of complex systems; they found that simple techniques as the weighted product method or the simple additive weighting method may perform better than several others MADM methods.

7 Experimental framework

The present Chapter focuses on the development of the experimental framework that makes up the theoretical ground based on which the actual BIM-based analytical tool has been integrated into the BIM project.

Before the actual coding of the tool, a careful Pavement Information Model was defined taking into account the expected life-cycle management results. Then, the main explanatory variables of the maintenance alternatives required a careful and broad data collection, which was carried out through the following steps:

- The definition of a laboratory experimental program to gather the necessary data in terms of mix composition and expected service life of the designed pavement solutions;
- The elaboration of a life cycle inventory and definition of environmental impact indicators for each process of the life cycle of different asphalt pavement solutions through consolidated LCI databases;
- The gathering of unit costs of materials, labour, machinery, disposal and maintenance processes from specific price lists of public works of Campania region (Italy) to support the definition of an LCC indicator for road management bodies.

Finally, the BIM-based management tool was developed setting up two key concepts: firstly, the methodological structure of the PMS and life-cycle based calculations and, second, the data exchange path between the BIM environment, the programming interface and external analysis tools, with particular focus on the informative content of the pavement BIM.

Figure 6 shows the flow diagram of the experimental framework aimed to:

- set up data templates (i.e. Excel spreadsheets) to import the needed information in the programming interface and speed up the informatization of the pavement information model;

- informatize the BIM of a road pavement through property sets definition;
- run calculations and update the property sets with the outcome of the maintenance algorithm and decision-making framework.

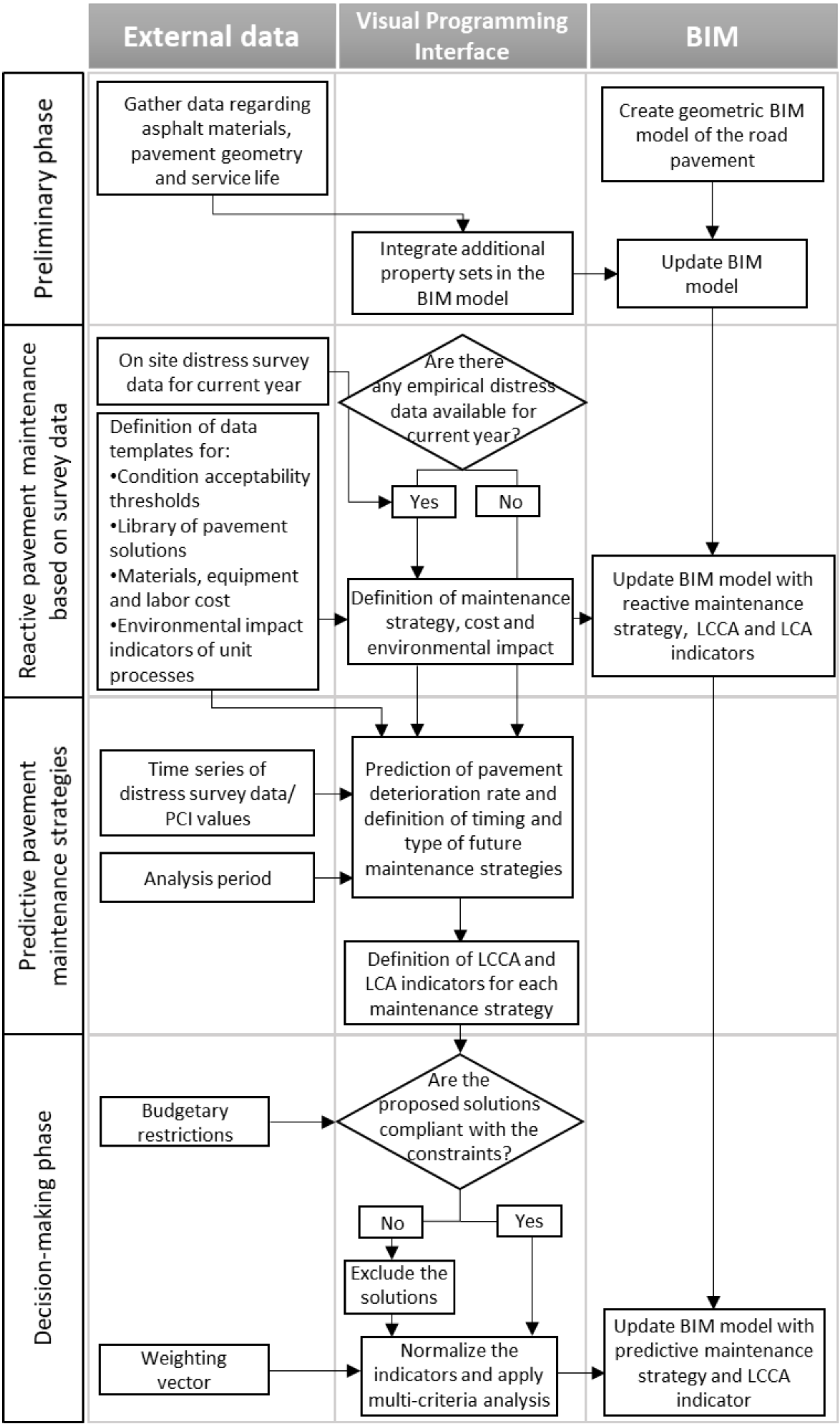


Figure 6 - Flow diagram of the BIM-based tool

7.1 Asphalt mixtures design and characterization

In the present work, several asphalt mixtures were designed using waste in partial substitution of natural ones [113], aiming firstly to lower the consumption of exhaustible natural resources and secondly to reduce and save pollutant emissions and the consequent effects on the cause-damage path that affects several environmental problems. The natural aggregates adopted in the study were limestone aggregates extracted from a quarry near Caserta in Southern Italy; their physical and mechanical properties are reported in Table 1.

Three wastes available locally (either supplied from external sources or produced directly in the construction site under analysis) were selected and investigated for subsequent reuse, as follows:

- RAP (Reclaimed Asphalt Pavement) was milled from the existing deteriorated asphalt pavement's wearing and binder layers and reused as a recycled coarse aggregate directly in the same construction site without any additional size reduction. In particular, given the high abrasion loss, experimentally determined through Los Angeles test (see Table 1), its preferred use was in substitution of the coarse aggregates in the base layer, which is less affected by traffic wearing actions. The RAP's size designation is 20 RA 0/16, where the number 20 indicates the smallest sieve size in mm through which 100% of the asphalt particles pass. According to UNI EN 13108-1. Since an asphalt mixture for the base layer should have an aggregate size distribution of 100% passing through a 31.5 mm sieve size. This means that the design of cold asphalt mixtures will require granulometric correction, produced by adding limestone aggregates.
- CDW (Construction and Demolition Waste) was supplied to the asphalt plant from a distance of 20 km and then milled until an aggregate distribution was reached that entirely passed at a 0.063 mm sieve size. As reported in Table 1, the CDW, in the form of a filler, has an equivalent sand equivalent to that of the limestone filler but a higher Rigden voids value than that of the limestone filler, suggesting higher optimum bitumen content but also higher stiffness of the optimized mixture, making it compliant with the requirements of a binder layer of a flexible pavement.
- JGW (Jet Grouting Waste) is initially produced as a mixed spoil of water, soil, and cement after the high-pressure injection of the cement grout for ground consolidation works; once it dries out, it is either supplied to the asphalt plant (that is 20 km away from the JGW production site) and milled for 2 h until the filler size is obtained, or cold-mixed with RAP directly on site. The physical properties shown in Table 1, in particular the higher Rigden voids value

than that of the limestone filler, suggest its potential to enhance the stiffness of the resulting optimized mixture.

Table 1 - Physical and mechanical properties of the limestone aggregates and waste materials after size reduction.

Property	Limestone	CDW	JGW	RAP
Los Angeles value (EN 1097-2)	16	–	–	24
Rigden voids (EN 1097-4)	51.4	55	53	–
Sand equivalent (EN 933-8)	80	76	60	71

In order to assess the compatibility of each waste material with the pollutant concentration limits established by the Italian Ministerial Decree issued on 5 February 1998, the RAP, CDW and JGW underwent an environmental compatibility analysis carried out through leaching test analysis (EN 12457-2), which quantified the concentrations of several pollutants, such as organic compounds and heavy metals leached into water by the waste sample. All the above-mentioned waste produced leaching concentrations lower than the quantification limits of the instruments; the substances that were found in relevant concentrations in the eluate, but still lower than the limits established by the Italian Ministerial Decree issued on 5 February 1998, are shown in Table 2.

Table 2 - Metals and organics concentrations above the quantification limits and pH of the eluate of the leaching test for the analyzed waste materials and limits set by M.D. issued on 5 February 1998.

Parameter	Unit	CDW	JGW	RAP	Limits of M.D. 5 February 1998
Zinc	mg/l	0.37	0.52	<0.01	3
Chloride	mg/l	65.78	53.17	16.30	100
Nitrate	mg/l	0.10	0.09	0.05	50
Fluoride	mg/l	<0.01	<0.01	0.52	1.5
Sulphate	mg/l	6.33	21.6	7.45	250
pH	–	5.02	10.92	6.95	12
COD [1]	mg/l	10.3	6.8	25.5	30

The aggregates were bonded using traditional asphalt-based binders. A 50/70 penetration-grade neat bitumen and a hard-modified bitumen with SBS virgin polymer were adopted as a natural binder for hot asphalt mixtures, respectively, as a benchmark for non-modified and polymer-modified asphalt mixtures; cationic bitumen emulsion and Portland cement 325 R were used as main binders into cold mixtures. The main properties of the binders are shown in Table 3.

Table 3 - Main properties of the neat and modified bitumen, bitumen emulsion, cement, and polymeric pellets.

Property	Unit	Value	Standard
	Neat bitumen		
Penetration @ 25 °C	dmm	68	UNI EN 1426
Softening point	°C	48.8	UNI EN 1427
Dynamic viscosity @ 150 °C	Pa s	0.25	UNI EN 13702
	Modified bitumen		
Penetration @ 25 °C	dmm	52	UNI EN 1426
Softening point	°C	87	UNI EN 1427
Dynamic viscosity @ 150 °C	Pa s	1.38	UNI EN 13702
	Bitumen emulsion		
Water content	%	40	UNI EN 1428
pH value	-	4.2	UNI EN 12850
Settling tendency at 7 days	%	5.8	UNI EN 12847
	Cement		
Initial setting time	min	112	UNI EN 196-3
Compressive strength	-	-	-
at 2 days	MPa	27.8	UNI EN 196-1
at 28 days	MPa	61.2	UNI EN 196-1
Volume constancy	mm	0.52	UNI EN 196-3
	Polymeric pellets		
Melting point	°C	180–190	-
Apparent density @ 25 °C	g/cm^3	0.40–0.60	-

In addition to Polymer Modified Bitumen, a polymer compound was adopted for dry asphalt mixture modification.

The polymer compound used in this study for asphalt dry modification was composed mainly of: (a) Polyethylene terephthalate (PET) recycled plastics subjected to a crushing treatment process to achieve final dimensions lower than 2 mm; (b) a mixture of optimized plastomeric polymers and copolymers such as Low-Density Polyethylene (LDPE) and EVA; and (c) additives of different types to ensure that the final polymer compound would be in the form of semi-smooth and flexible granules. The main properties in terms of melting point and apparent density are displayed in Table 3.

After the definition of the basic physical and mechanical features of the raw materials, several asphalt mixtures were designed using both hot and cold production technologies according to two different design procedures.

Asphalt mix design is an iterative procedure that consists of defining the optimum content of the components of the mixture to obtain volumetric and mechanical properties compliant with both international technical standards and local technical specifications.

The first step in the mix design procedure for all the asphalt mixtures under analysis consists in defining an aggregate size distribution complying with the layer’s specific aggregate size requirements set by UNI EN 13108-1 and SUPERPAVE [114]. Subsequently, all the specimens, prepared with different binder contents per aggregate weight, were compacted using a gyratory compactor, which, by applying low static compression and shear actions, reproduces field compaction effort. In detail, the mix design procedures carried out for the design of the optimum composition of hot and cold asphalt mixtures were as follows:

- Firstly, the same grading curve was designed for all the asphalt mixtures for the binder layer (HMA, HMAC, HMMA, PMA) and the same for the mixtures for the base layer (HMA, HMAJ) aiming to maximize the amount of secondary materials in each mixture without compromising the mechanical performance of the material. Then, the Optimum Bitumen Content (OBC) was defined following the SUPERPAVE procedure [114]. The results shown in Tables Table 4 Table 5 give a broad view of the composition of the hot asphalt mixtures under analysis.

- Moving on to the mix design of the cold asphalt mixture for base layer (CMRA), the aggregate size distribution was established in order to maximize the amount of RAP replacing natural aggregates. Since the RAP grading curve did not fall within the limits defined by UNI EN 13108-1 and SUPERPAVE control points, granulometric correction was required as foreseeable from its size designation. The aggregate composition of the CMRA solution contained 70% RAP and 30% natural aggregates (Table 5). Once the composition of the grading curve had been established on the basis of the range suggested in the literature [115], the optimum combination of cement (in a range between 0.5 and 1.5% by the weight of the total grading composition with an increment of 0.5%) and water (in a range between 4 and 6% by the weight of the total grading composition with an increment of 1%) was obtained in order to maximize the workability of the cold mixture and maximize the final specific gravity of the cold mixture. The last phase of the cold bituminous mixture optimization focused on finding the optimum bitumen emulsion content in a range between 3 and 6% with increments of 0.25% by the total aggregate weight [116]. The results in Table 5 show the optimum content of water, cement and bitumen emulsion, equaling 5, 1.5, and 3.75% by the total weight of the aggregates.

Table 4 - Aggregate size distribution and mix design results for the hot asphalt mixtures for the binder layer.

Mixture ID	Properties	HMA	HMAC	HMMA	PMA
Mix composition	Limestone 12/18 mm	25%	23%	25%	25%
	Limestone 6/12 mm	33%	29%	33%	33%
	Limestone 3/6 mm	–	13%		
	Limestone sand	38%	31%	38%	38%
	Limestone filler	4%	–	4%	4%
	CDW	–	4%	–	–
	Bitumen wa.% *	5.00%	5.75%	5.00%	5.00%
	Polymer pellets wb.% **	–	–	–	5.00%
Volumetric properties	% air voids	4.00%	4.20%	4.00%	4.20%
	Specific gravity, g·cm^{-3}	2.52	2.48	2.50	2.50

Table 5 - Aggregate size distribution and mix design results for the asphalt mixtures for the base layer.

Mixture ID	Properties	HMA	HMAJ	CMRA
Mix composition	Limestone 18/31.5 mm	9%	9%	16%
	Limestone 12/18 mm	32%	32%	7%
	Limestone 6/12 mm	31%	31%	–
	Limestone sand	21%	21%	–
	Limestone filler	7%	–	7%
	JGW	–	7%	-
	RAP	–	–	70%
	Bitumen wa.%	4.50%	4.85%	–
	Bituminous emulsion wa.%	–	–	3.75%
	Cement wa.%	–	–	1.50%
Volumetric properties	Air voids	4.00%	3.90%	9.00%
	Specific gravity, g·cm^{-3}	2.35	2.37	2.49

7.2 Design of alternative maintenance solutions

Asphalt pavement distresses are strictly linked to the ability of the pavement layers to spread the load applied by the vehicle's axles passages and to control the stress–strain state induced in the asphalt materials. One of the mechanical tests that best represents the dynamic response of asphalt materials under repeated loading is the Indirect Tensile Stiffness Modulus (ITSM) test performed according to EN 12697-26—Annex C.

The test was performed at four temperatures (5, 10, 20, and 30 °C), which represent the average temperature conditions of the pavement in Southern Italy across the four seasons (winter, spring, autumn, and summer, respectively).

The results of the stiffness modulus characterization are reported in Table 6 for all the asphalt mixtures under exam and were of fundamental importance during the subsequent design of asphalt pavement configurations according to rational design criteria that rely on the linear elastic constitutive laws for each asphalt material. Each pavement solution was then embedded into a pavement library and fed to the BIM-based PMS tool.

Table 6 - Indirect tensile stiffness modulus results at 5, 10, 20, and 30 °C for the asphalt mixtures under analysis.

Asphalt Layer	Mixture Identification	ITSM (MPa) – EN 12697-26 Annex C				
		5 °C	10 °C	20 °C	30 °C	ν
Wearing course	HMA	10013	6931	3077	1355	0.35
Binder layer	HMA	12780	8279	5299	1818	0.35
	HMAC	11921	8120	5301	1977	0.35
	HMMA	25136	15391	8613	3402	0.35
	PMA	31143	16498	9582	2897	0.35
Base layer	HMA	15500	10220	5952	2960	0.35
	HMAJ	17649	11725	6826	3204	0.35
	CMRA	9101	6380	3267	2203	0.35

The first step supporting road pavement design workflow is the definition of a structural model, where each material is characterized by two main mechanical features: the stiffness modulus (ITSM) and the Poisson's ratio. In order to define the consequent stress–strain state, the pavement is subjected to the equivalent standard axle load (ESAL); the design thickness required by each pavement layer must be such to contain the tensile stresses at the bottom of the base layer, which leads to fatigue cracking, and the compression stresses at the top of the asphalt layers, responsible for the rutting phenomenon.

The main traffic and load data are reported in Table 7.

Table 7 – Traffic and load data for asphalt pavement design

Parameter	Units	Value
Road category	-	C
AADT - Annual Average Daily Traffic	1/d	5000
Rate of heavy vehicles	%	5
R – Traffic growth rate	%	3
Traffic spectrum	-	Road category C traffic spectrum [117]
ESALS in 20 years	-	1'633'384

In the present work, the asphalt mixtures designed during the experimental phase are then used as design solutions for the binder and base layer of flexible pavements; the remaining asphalt layer, i.e. the wearing course, is made up of a traditional HMA, whose mix design and mechanical characterization was carried out assessed in Russo et al. [118] and Veropalumbo et al. [119]. The subbase layer is made of granular mixture having a Young elastic modulus of 116 MPa, while the subgrade has a deformation modulus (Md) equal to 50 MPa.

In detail, the *m* asphalt mixtures for the binder layer (with m equal to 4) and the *n* asphalt mixtures for the base layer (with n equal to 3) are combined into mxn solutions, that is, 12 pavement stratigraphies.

The cumulative fatigue damage (FD), which must be kept below 1 to avoid excessive deterioration of the surface quality (FD equal to 1 means that 10% of the lane area is covered in cracks), is determined as the sum of the seasonal Di, namely the share of relative damage produced by the ESALs passings during the i-th season, according to the Miner law, which is reported in Equation (14).

$$CD = \sum_{i=1}^{S} \frac{n_i}{N_i} \tag{14}$$

Where:

n_i is the number of ESAL passages in the i-th season, which is computed through the AASHTO Design method [97] supposing that the ESAL passings are evenly distributed between the four seasons;

N_i is the number of ESAL passages that leads to an extension of fatigue cracking damage up to 10% of the lane area of the road pavement, determined according to the Asphalt Institute fatigue prediction law [83] through the average ITSM and the tensile strain at the bottom of the base layer resulting from the linear elastic multilayer model.

The rut depth (R) at the end of the service life, which should never be deeper than 2 cm for Italian suburban roads, is predicted through the Vaerstaten law, as shown in Equation (15).

$$RD = \sum_{j} \sum_{i} \varepsilon_{ij} \cdot h_j \tag{15}$$

Where:

ε_{ij} is the permanent deformation in the i-th season that is accumulated in the j-th asphalt layer of the pavement after the mentioned ESAL passings, determined according to the Kaloush and Witczak model [84] based on the vertical compressive strain obtained from the linear elastic multilayer model;

h_j is the thickness of the j-th asphalt layer.

The pavement design results are reported in Table 8 in terms of thicknesses of the asphalt layer, the mean and standard deviation of the service life, FD, and R. It is worth mentioning that the combination of HMMA binder layer with cold recycled mixture for the base layer (CMRA) posed some questions about the structural compatibility of these materials since the application of the ESAL induced a tensile stress state in the binder layer that was not compatible with the structural integrity of the pavement in the long term. Therefore, an alternative pavement stratigraphy was designed for the combination of HMMA and CMRA (see Table 8).

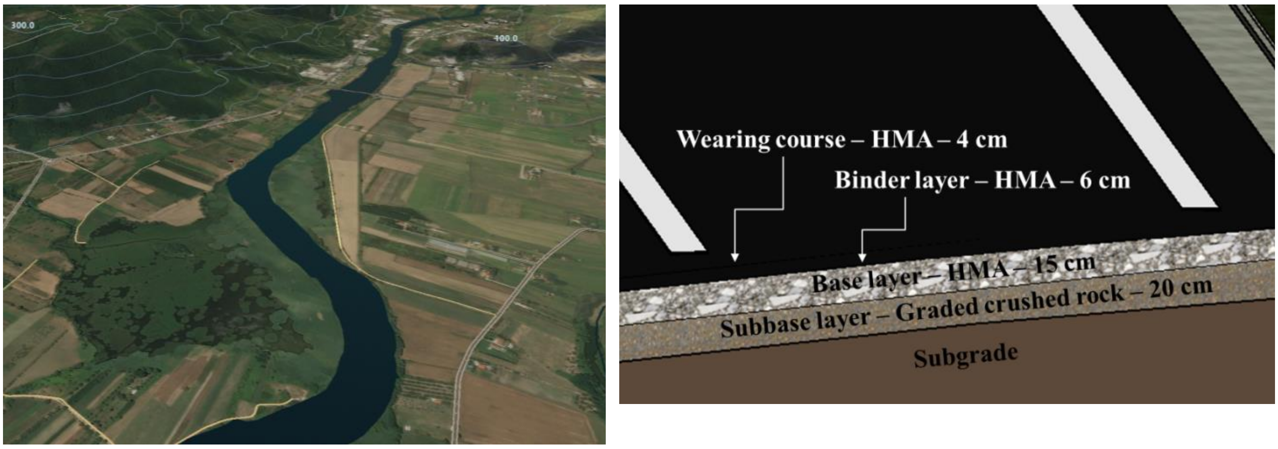
Table 8 - Asphalt pavement configurations, thicknesses of the asphalt layers, mean (μ) and standard deviation (σ) of the service life, cumulative fatigue damage (FD), and rut depth (R).

<table>
<tr><th rowspan="2">Asphalt Pavement Configurations [1]</th><th colspan="3">Layers' thickness (cm)</th><th colspan="2">Service life (y)</th><th colspan="2">FD (−)</th><th colspan="2">R (cm)</th></tr>
<tr><th>Wearing Course</th><th>Binder Layer</th><th>Base Layer</th><th>μ</th><th>σ</th><th>μ</th><th>σ</th><th>μ</th><th>σ</th></tr>
<tr><td>HMA-HMA-HMA
HMA-HMAC-HMA
HMA-HMMA-HMA
HMA-PMA-HMA
HMA-HMA-HMAJ
HMA-HMAC-HMAJ
HMA-HMMA-HMAJ
HMA-PMA-HMAJ</td><td>4</td><td>5</td><td>20</td><td>24.1</td><td>2.6</td><td>0.97</td><td>0.03</td><td>0.29</td><td>0.04</td></tr>
<tr><td>HMA-HMA-CMRA
HMA-HMAC-CMRA
HMA-PMA-CMRA</td><td>4</td><td>7</td><td>20</td><td>19.7</td><td>1.8</td><td>0.96</td><td>0.01</td><td>0.76</td><td>0.06</td></tr>
<tr><td>HMA-HMMA-CMRA</td><td>4</td><td>5</td><td>21</td><td>20</td><td>–</td><td>0.95</td><td>–</td><td>0.67</td><td>–</td></tr>
</table>

[1] Asphalt pavement configuration is expressed as: wearing course material ID – binder layer material ID – base layer material ID.

7.3 Main features of the case study

A 1 km-long section of a suburban road (width equal to 10.5 m) located near Naples (Italy), for which the time series of PCI surveys was available, was selected as the illustrative case study of the developed methodology. The conventional BIM modelling phase included the 3D digital terrain model, the horizontal alignment, vertical profiles and road cross-sections, which concurred to the generation of the 3D parametric model of the road (see Figure 7 a) and b)) [120].



a) b)

Figure 7 - Features of the BIM model: a) Digital Terrain Model and b) Cross section of the road pavement reproducing in-situ conditions

The set of maintenance alternatives included, besides the conventional HMA, modified asphalt mixtures (polymer modified asphalts (PMAs), conventional asphalt mixtures with polymer modified bitumen (PMB), HMAs with secondary raw materials in substitution of natural aggregates, as well as sustainable solutions like in-place recycled cold mix asphalts (CMAs) for either the binder or the base layers. Table 9 summarizes the set of solutions under analysis as they were imported through the data template “pavement library” in the BIM environment. The reference analysis period of case study is equal to 50 y.

Table 9 - Overview of the maintenance alternatives considered for the application of the methodology

Type of maintenance intervention	Description	Expected frequency of maintenance interventions	Materials' alternatives in the case study
Local repairs	Potholes repair (patching)	1-2 years	Asphalt mixture depending on the pothole depth
	Crack sealing	1-2 years	Asphalt sealants
Surface rehabilitation	Milling and reconstruction of the wearing course	3-5 years	HMA – wearing course
Deep rehabilitation	Milling and reconstruction of the wearing course and binder layer	5-15 years	HMA – wearing course
			HMA – binder layer
			HMAC – binder layer
			PMA – binder layer
			HMMA – binder layer
Reconstruction	Milling and reconstruction of the asphalt layers (base, binder and wearing course)	10-30 years	HMA – wearing course
			HMA – binder layer
			HMAC – binder layer
			PMA – binder layer
			HMMA – binder layer
			HMA – base layer
			CMRA – base layer
			HMAJ – base layer

7.4 Distress survey data and condition indicators

Looking now at the elaboration of the PMS, it starts from the assessment of the conditions of the pavement structure, carried out in this work through visual and instrumental survey in situ of the asphalt distresses according to [87].

The status indicators adopted in the maintenance plan were the following: a) the Pavement Condition Index (PCI), a global indicator of the structural conditions of the pavement with numerical value between 0 (completely failed road surface) and 100 (perfect road condition) that is calculated from a visual survey of pavement distress on a sample of the network, b) the accumulated fatigue damage predicted through [83], c) the accumulated rut depth predicted through [84] and d) several sets of rules and actions to be adopted on the basis of the type, extension and severity of the surveyed distresses.

The main input to assess present pavement condition on the pavement section under analysis is the synthetic survey sheet (see Table 10), which also makes up one of the data templates imported to the BIM environment to perform PCI calculation and define the reactive maintenance strategy.

Table 10 - Synthetic survey sheet

Distress ID	Severity	Units	Value
FatigueCrackingL	L	m^2	145.8
FatigueCrackingM	M	m^2	411.36
FatigueCrackingH	H	m^2	5407.44
BlockCrackingL	L	m^2	508.8
BlockCrackingM	M	m^2	0
BlockCrackingH	H	m^2	600
EdgeCrackingL	L	m	0
EdgeCrackingM	M	m	0
EdgeCrackingH	H	m	0
LongCrackingL	L	m	0
LongCrackingM	M	m	4720.8
LongCrackingH	H	m	0
RefCrackingL	L	m	0
RefCrackingM	M	m	0
RefCrackingH	H	m	0
TransvCrackingL	L	m	0
TransvCrackingM	M	m	500.4
TransvCrackingH	H	m	84
DeterioratedPatchL	L	m^2	1011
DeterioratedPatchM	M	m^2	1993.92
DeterioratedPatchH	H	m^2	366.6
PotholeL	L	m^2	2.4
PotholeM	M	m^2	37.08
PotholeH	H	m^2	11.04
RuttingL	L	m^2	0
RuttingM	M	m^2	0
RuttingH	H	m^2	0
Shoving		m^2	0
Bleeding		m^2	0
PolishedAggregates		m^2	6996
Raveling		m^2	0
LaneShoulderDropoff		m	0

7.5 Reactive maintenance strategy based on distresses

Aiming to set up an automated reactive maintenance algorithm, a rigid set of rules and actions was originally developed in the present work basing on the type, severity and density of each distress identified according to the Distress Identification Manual for the long-term pavement performance program [87]. In detail, Figure 8 shows the logical flow implemented in the maintenance algorithm, starting from the evaluation of the distress categories and ending once identified the proper maintenance strategy. As reported in Figure 8, the choice of the proper maintenance strategy takes into account the traditional PCI thresholds [121]; additionally, the type, extension and severity of certain distress categories are taken into account to assess whether the specific maintenance intervention should be applied to the whole pavement surface, or limited to a portion of the surface to resolve localized failures (e.g. patching, sealing) and restore a high PCI value over the whole pavement surface.

In particular, three main maintenance interventions were triggered by the PCI values (see Figure 8):

- surface rehabilitation: it implied the milling and reconstruction of the wearing course and the assessment of the condition of the binder layer (e.g. extraction of core samples from the binder layer to test the stiffness modulus, in-situ testing to measure the bearing capacity of the deeper layers etc.);
- deep rehabilitation: it consists of the milling and reconstruction of the wearing course and binder layer (and relative tests applied to measure the structural capacity of the base layer, e.g. coring of the base layer and stiffness measurement);
- reconstruction: it involves the full reconstruction of the asphalt layers (wearing, binder and base layer) and subsequent control of the subbase bearing capacity.

Instead, PCI values above 85 implied no maintenance interventions due to good quality of the pavement surface.

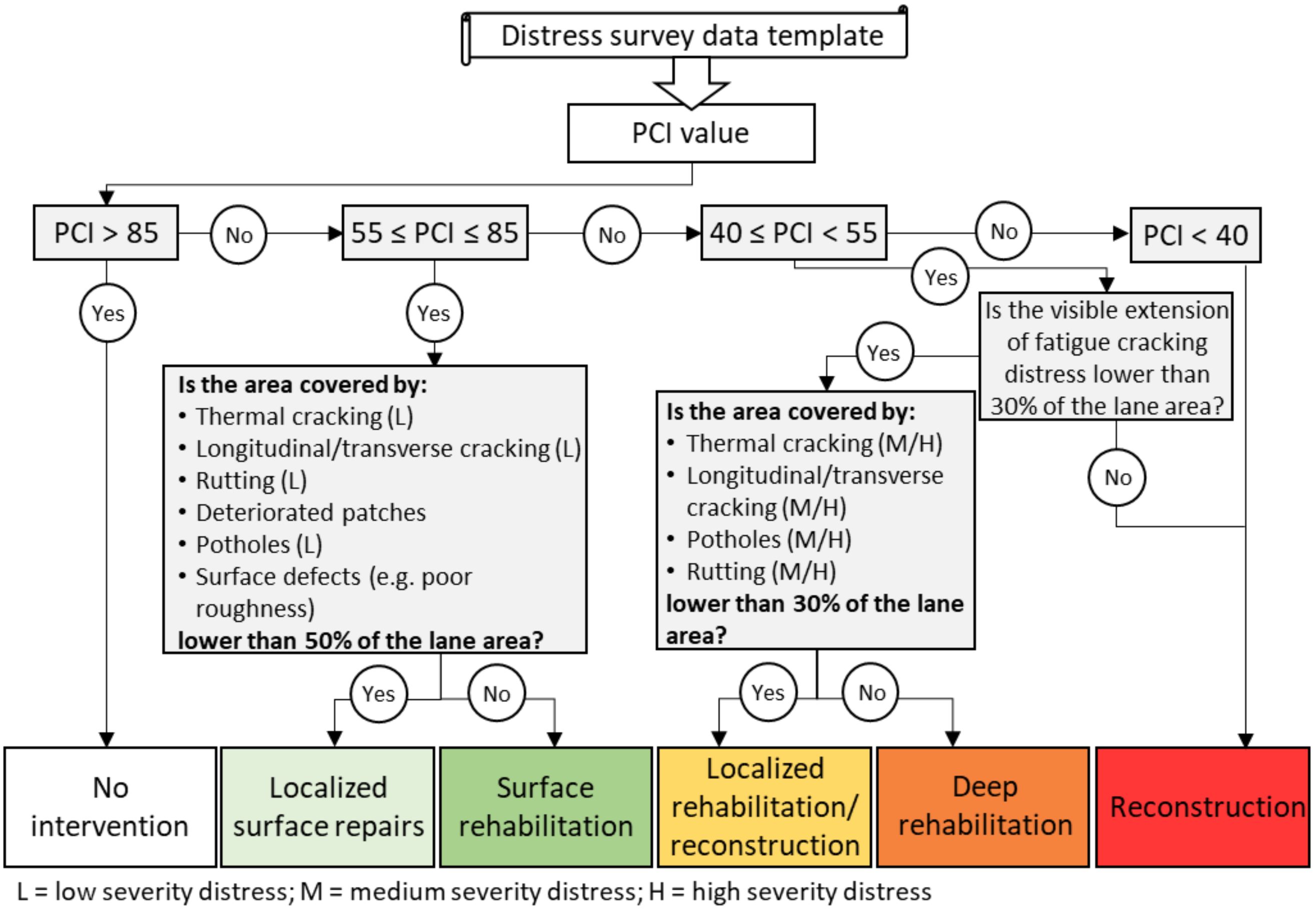


Figure 8 - Reactive maintenance strategy based on the actual PCI value and distress survey data

The algorithm is semi-automatic because it requires the intervention of the user, who must enter as input the identification codes of the spatial and temporal units of control, in other words he must indicate the homogeneous region of road taken into consideration, with a certain length, and the current year of analysis. These inputs are needed to filter the data in the source database, which is imported as an Excel file. The reading of the database consists of selecting the distress survey data related to the sample unit and the control year indicated by the user. Another input to the algorithm is the geometry of the road section, which is imported directly from the parametric section of the BIM of the pavement [122].

The degradation data used are the measure of the areas involved in certain degradation phenomena: fatigue cracking, block cracking, edge cracking, longitudinal cracking, transversal cracking, patch, potholes, rutting, bleeding. For each parameter, the survey distinguishes between three levels of severity: high, medium, and low (see Figure 8).

The algorithm follows three systems of rules for the definition of the most appropriate maintenance strategy:

1. it considers the single parameters, and therefore the character of the single damages, and associates a specific type of intervention, namely “local Intervention”;
2. it considers the superposition of the effects of the different damage parameters;
3. it calculates the PCI (Pavement Condition Index), to assess if to overall condition of the pavement section requires a different intervention compared to those resulting from the analysis of each distress.

7.6 Predictive maintenance strategy

The prediction of the pavement condition over time was carried out through decay curves, such as those based on the mentioned empirical fatigue and rutting damage accumulation laws, but also, where historical PCI series of data were available, through the interpolation of these data. Each of these parameters was associated with one or more threshold values corresponding to the need for superficial, deep rehabilitation or full reconstruction. Then, for each maintenance strategy, the number of years after which a maintenance intervention will be necessary was identified as the minimum number of years required to reach the respective limit condition for each condition indicator, respectively using Equations (16), (17) and (18) for the surface rehabilitation, deep rehabilitation or reconstruction intervention (see Figure 9).

$$N_{SR} = N_{SR,PCI} \tag{16}$$

$$N_{DR} = \min\left(N_{DR,PCI}; N_{DR,U}\right) \tag{17}$$

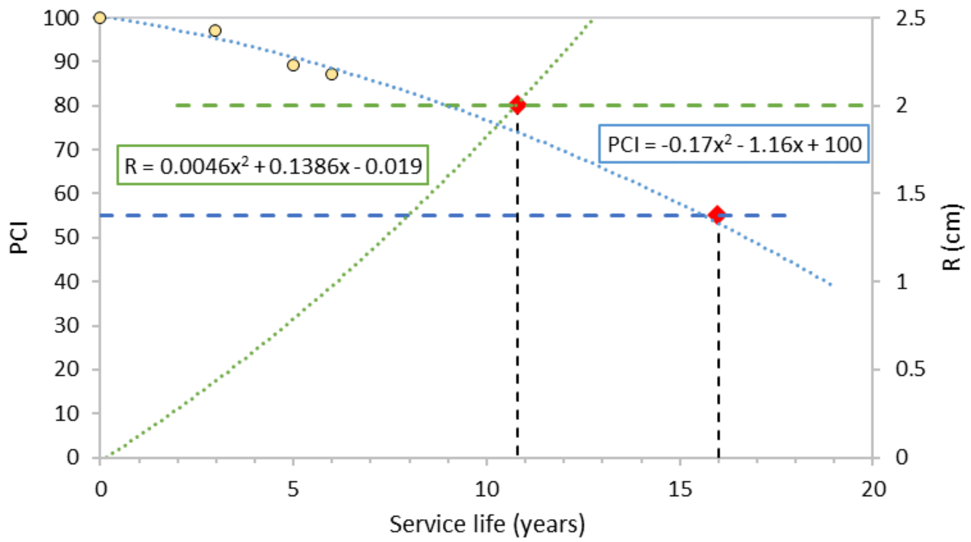
$$N_{RE} = \min\left(N_{RE,PCI}; N_{RE,FD}\right) \tag{18}$$

Where:

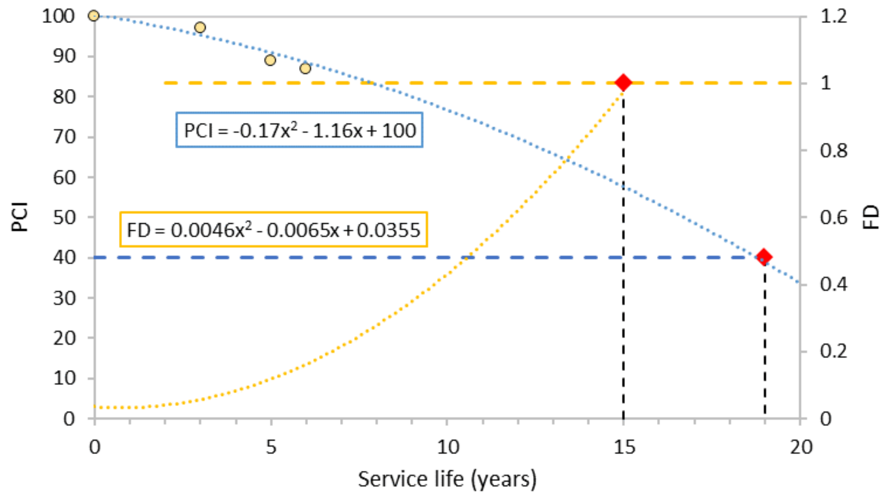
N_{SR} is the number of years before the next surface rehabilitation intervention, which is equal to the number of years before reaching the predicted PCI value of 85 ($N_{SR,PCI}$);

N_{DR} is the number of years before the next deep rehabilitation intervention, which is selected as the minimum between the number of years before reaching either a PCI value of 54 ($N_{DR,PCI}$) or an accumulated rut depth equal to 2 cm ($N_{DR,U}$);

$N_{RE,PCI}$ is the number of years before the next reconstruction intervention, which is selected as the minimum between the number of years before reaching either a PCI value of 39 ($N_{RE,FD}$) or an accumulated fatigue damage value equal to 1 ($N_{RE,FD}$).



a)



b)

Figure 9 - Examples of trigger conditions for deep rehabilitation (a) and reconstruction (b) interventions

7.7 Analytical approach for the estimation of environmental impact indicators

At this point it is necessary to assess the solutions in terms of the environmental and economic dimension of the life cycle. In particular, the solutions have been characterized from an environmental point of view through the LCA procedure, intended as an objective methodology for assessing and quantifying the energy and environmental loads associated with a product along the whole life cycle, from the acquisition of raw materials up to the end of the useful life (EN 14040).

Generally, researchers identify two ways to integrate environmental criteria into the bidding process: the first one consists of supplying each component/equipment/material accompanied by an EPD (EN 15804), namely the set of quantitative environmental indicators that will be assembled downstream to define the overall environmental burdens of the life cycle of the infrastructure; the second one, which is currently in use since no legal requirements exist for producers, is that all the burden of the environmental analysis and assessment falls, downstream in the bidding process, on the engineer that should conduct a thorough investigation to retrieve as much primary data as possible. So, the LCA procedure was integrated into the PMS by automating the LCA calculations though several analytic expressions, each one involving a number of parameters: a) customizable property sets associated to the pavement objects and imported into the programming environment and b) other parameters, collected into specific data templates and imported into the same programming environment [123].

The first constitutive phase of the life cycle of an asphalt pavement is the production of raw materials that make up the asphalt mixture (see Equation 19); for example, a traditional HMA is made up of natural aggregates (coarse particles, sand and filler), which are typically extracted from natural rock benches and manufactured according to subsequent steps of crushing and sieving into dedicated plants and then transported to the asphalt plant, where they are stockpiled in dedicated areas.

Then, traditional HMAs are typically manufactured into centralized asphalt plants, which are powered by electricity and burn fuels (i.e. natural gas) to heat the aggregates; then, aggregates, filler and bitumen are mixed and discharged into dump trucks and transported to the construction site (see Equation 20). The construction of the asphalt pavement (see Equation 21) involves the milling machine to remove the existing distressed layers, the paver machine and one or more rollers to provide the desired compaction of each pavement layer, or eventually the crack sealing equipment; the removed materials are then landfilled according to the recycling rate of the mixture to be laid. The maintenance phase is performed repeatedly within the analysis period according to the adopted maintenance approach, and involves the previous productive and constructive stages (see Equation 22). Lastly, once the whole pavement structure has reached the end of its service life, the demolition and landfilling/recycling of the distressed asphalt pavement takes place (see Equation 23).

$$EI_x^{RMP} = \sum_{i=1}^{a} \sum_{j=1}^{b} (Q_{i,j}^{M} \cdot EI_{j,x}^{M} + Q_{i,j}^{M} \cdot D_j^{M} \cdot EI_{j,x}^{T}) \tag{19}$$

$$EI_x^{A} = \sum_{i=1}^{a} f_i \cdot \left(Q_i^{A} \cdot EI_x^{AP} + Q_i^{A} \cdot D^{A} \cdot EI_x^{T}\right) \tag{20}$$

$$EI_x^{CON} = \sum_{i=1}^{a} \sum_{k=1}^{c} \left[\frac{Q_i^{A,ES}}{P^M} \cdot EI_{k,x}^{M} + Q_i^{A,ES} \cdot P_i^{W} \cdot EI_x^{W} + Q_i^{A,ES} \cdot \left(1 - P_i^{W}\right) \cdot EI_x^{R} + \frac{Q_i^{A}}{P_{i,k}^{E}} \cdot EI_{k,x}^{C}\right] \tag{21}$$

$$EI_x^{MN} = \sum_{i=1}^{a} \left[\left(EI_{i,x}^{RMP} + EI_{i,x}^{A} + EI_{i,x}^{C}\right) \cdot m_i\right] \tag{22}$$

$$EI_x^{EOL} = \sum_{i=1}^{a} [Q_i^{A} \cdot D^{W} \cdot EI_x^{T} + Q_i^{A} \cdot P_i^{W} \cdot EI_x^{W} + Q_i^{A} \cdot (1 - P_i^{W}) \cdot EI_x^{R}] \tag{23}$$

Where:

- a is a counter that refers to the specific asphalt layer of the pavement and is included in the range [1,3];
- b is a counter of the raw materials included in each mixture (e.i. coarse aggregates, sand, filler, binders, additives, polymers, RAP, other recycled aggregates). The range of variation of b varies according to the alternative mixtures and their relative components. In the present work, b is included in the range [1, 8];
- c is a counter of the number of operating equipment for both milling of existing distressed layers, laying and compaction of HMAs or cold-in place recycling of CMRAs. In the present work, c is in the range [1, 9];
- EI_x^{RMP} is the x-th environmental indicator (EI) related to the production and supply of primary or secondary raw materials;
- $EI_{j,x}^{M}$ is the x-th EI related to the production of 1 tonne of the j-th raw material;
- $EI_{j,x}^{T}$ is the x-th EI of the transportation of 1 tonne of the j-th material for 1 km (fine aggregates are hauled by tanker trucks, while coarser aggregates and asphalt mixtures are hauled by dump trucks);
- $Q_{i,j}^{M}$ is the mass of the j-th raw material in the i-th asphalt layer [t];
- D_j^{M} is the distance of the production facility of the j-th raw material from the asphalt plant [km];
- Q_i^{A} is the mass of asphalt mixture produced to build the i-th pavement layer [t];
- EI_x^{A} is the x-th EI of the in-plant asphalt mixture manufacturing and supply to the construction site;
- f_i is a dummy variable, equal to 1 when the i-th asphalt mixture is produced in the asphalt plant, 0 if the asphalt mixture is produced in place;
- EI_x^{AP} is the x-th EI related to the in-plant manufacturing process of 1 tonne of asphalt mixture;
- D^{A} is the distance of the asphalt production from the construction site [km];
- EI_x^{CON} is the x-th EI of the pavement construction operations;

- $Q_i^{A,ES}$ is the volume of the existing i-th asphalt layer to be milled for the new construction/maintenance intervention [m^3];
- P^M is the productivity of the milling operations, where the milling machine and the dump truck work in series [m^3/h];
- $EI_{k,x}^M$ is the x-th EI of the k-th milling equipment (milling machine and dump truck) for each operating hour;
- P_i^W is the percentage by mass of the i-th existing milled asphalt layer that is disposed in landfill;
- EI_x^W is the x-th EI for 1 tonne of milled asphalt pavement disposed in the landfill;
- EI_x^R is the x-th EI for 1 tonne of milled asphalt pavement recycled as RAP;
- $P_{i,k}^E$ is the productivity of the k-th construction equipment used to build the i-th asphalt layer (grader, paver, and roller for hot construction, grader, pulvimixer, steel and pneumatic rollers for cold recycled layers) [t, m^2 or m^3/h];
- $EI_{k,x}^C$ is the x-th EI of the k-th construction equipment for each operating hour;
- EI_x^{MN} is the x-th EI of the whole maintenance process in the analysis period;
- m_i is the number or maintenance interventions in the analysis period;
- EI_x^{EOL} is the x-th EI of the end-of-life scenario;
- D^W is the distance from the construction site to the landfill [km].

The EIs were estimated according to midpoint ReCiPe 2016 Hierarchist (H) method [124], that converts input and output flows into midpoint damage categories that refer to specific environmental issues [125]; each of them contributes, at the end of the damage path, to easily-understandable and interpretable broader societal issues.

7.8 Analytical approach for the estimation of the life cycle costs

A similar formulation was developed for the life cycle costs incurred by the road managing agency.

The FHWA recommends to analyse pavement alternatives over the same analysis period and consider the remaining value of each alternative at the end of the analysis period (i.e., salvage value of materials or value of remaining service life) as a "benefit" or "negative cost" [126]. Therefore, the life cycle cost indicator was here defined using the net present value method [53], obtained as the sum of the discounted cost components on the basis of a discount rate r and subtracting the residual value of the pavement at the end of the analysis period, which is not necessarily equal to the useful life. The overall life cycle agency's cost indicator (LCCA) was expressed using Equation 24, whose terms are respectively expressed by Equation 25 (construction costs), Equation 26 (maintenance costs), Equation 27 (end of life costs) and Equation 28 (salvage value).

$$LCCA = C^{CON} + C^{M} + C^{EOL} - S\frac{1}{(1+r)^{T}} \tag{24}$$

$$C^{CON} = \sum_{i=1}^{a}\left(\sum_{j=1}^{b} Q_{i,j}^{M} \cdot C_{j}^{M} + \sum_{k=1}^{c}\left(\frac{Q_{i}^{A}}{P_{i,k}^{E}} \cdot C_{k}^{E} + \sum_{l=1}^{d}\frac{Q_{i}^{A}}{P_{i,k,l}^{E}} \cdot n_{k,l}^{W} C_{l}^{W}\right)\right) \tag{25}$$

$$C^{MN} = \sum_{i=1}^{a}\left[\left(\sum_{j=1}^{b} Q_{i,j}^{M} \cdot C_{j}^{M} + \sum_{k=1}^{c}\left(\frac{Q_{i}^{A}}{P_{i,k}^{E}} \cdot C_{k}^{E} + \sum_{l=1}^{d}\frac{Q_{i}^{A}}{P_{i,k,l}^{E}} \cdot n_{k,l}^{W} C_{l}^{W}\right)\right) \cdot m_{i} \cdot \frac{1}{(1+r)^{n_{i}}}\right] \tag{26}$$

$$C^{EOL} = \sum_{i=1}^{a}\left[\left(Q_{i}^{A} \cdot D^{W} \cdot C^{T}\right) + \left(Q_{i}^{A} \cdot P_{i}^{W} \cdot C^{W}\right) + \left(Q_{i}^{A} \cdot (1 - P_{i}^{W}) \cdot C^{R}\right)\right] \cdot \frac{1}{(1+r)^{n}} \tag{27}$$

$$S = \left(1 - \frac{L_{a,S}}{L_{a,A}}\right) \cdot C_{a}^{M} \tag{28}$$

Where:

- a, b and c have the same meaning of those in Equations 19-23;
- C^{CON} is the net present value of the construction cost of the pavement [€];
- C^{MN} is the net present value of the maintenance cost of the pavement [€];
- C^{EOL} is the net present value of the end of life cost of the pavement [€];
- S is the salvage value of the pavement at the end of the analysis period [€];
- C_{j}^{M} is the unit supply cost of the j-th raw material [€/t];
- C_{k}^{E} is the hourly cost of the k-th construction equipment [€/h];
- $P_{i,k,l}^{E}$ is the is the productivity of the k-th construction equipment used to build the i-th asphalt layer referred to the l-th category of workers (skilled, specialized etc.) [t, m^2 or m^3/h/worker];

- $n_{k,l}^{W}$ is the number of workers of the l-th category required to handle the k-th construction equipment;
- C_l^{W} is the hourly cost of the l-th category of workers [€/h];
- m_i is the number of maintenance interventions involving the reconstruction of the i-th asphalt layer during the analysis period;
- n_i is the number of years after which a maintenance intervention should be carried out [y];
- $L_{a,S}$ is the expected service life of the a-th maintenance intervention [y].
- $L_{a,A}$ is analysis life of the a-th maintenance intervention, i.e. difference between the year of construction of the a-th maintenance intervention and the year of termination of the analysis period [y].

7.9 Decision-making and budgetary restrictions

The MADM is a discipline aimed at supporting decision makers when dealing with multiple solutions and heterogeneous and conflicting assessments, allowing for a compromise solution to be obtained in a transparent manner.

The set of performance indicators (i.e. condition indicators, agency's cost and environmental impact indicators of the life cycle) characterized for each asphalt solution and each unit sample makes up the decision matrix for selecting the best alternative and defining a priority score for each maintenance intervention. [127]

In the present study, a total of 22 indicators, sum of 18 environmental impact indicators and 1 life cycle cost indicator and 3 performance/damage indicators, were used as the criteria of the analysis, and the alternatives of the analysis were, in the first case, the 12 alternative reconstruction solutions and the 4 rehabilitation alternatives.

A *decision matrix A* was obtained considering the set of maintenance alternatives $M_1 = \{1, \ldots j, \ldots m\}$ with *m* = 16 and the set of criteria $I = \{1, \ldots i, \ldots l\}$ with *l* equal to 22, as shown in Equation (29).

With the entry a_{ij} of A we refer to the value of the *i*-th criteria related to the *j*-th alternative maintenance solution.

$$\underset{22\times 12}{A} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,12} \\ \vdots & a_{ij} & \vdots \\ a_{22,1} & \cdots & a_{22,12} \end{pmatrix} \tag{29}$$

Since all the criteria reported into the decision matrix has different units of measurements, a normalization was carried out to obtain the normalized decision matrix N (see Equation (32)). For the criteria where high value represents the best performance (PCI), the normalization occurred by using Equation (30), while in the case of R, FD, LCC indicator and the 18 environmental impact indicators, where the lowest values represent the best performance, the Equation (31) was adopted.

$$n_{1,ij} = \frac{a_{ij}}{\max a_i}\,; \tag{30}$$

$$n_{1,ij} = \frac{\min a_i}{a_{ij}}\,; \tag{31}$$

Where:

- n_{ij} is the normalized *i*-th criteria in the range [1;22] for *j*-th maintenance solution;
- $\max a_i$ and $\min a_i$ are the maximum and minimum values of the *i*-th criteria, respectively, among all maintenance solutions.

$$\underset{22\times 16}{N} = \begin{pmatrix} n_{1,1} & \cdots & n_{1,16} \\ \vdots & n_{ij} & \vdots \\ n_{22,1} & \cdots & n_{22,16} \end{pmatrix} \tag{32}$$

The decision matrix is structured as reported in Table 11

Table 11 - General structure of the decision matrix

Maintenance alternative	**Condition indicators**			**LCC**	**LCA**		
1	$PC_{1,1}$	…	$PC_{1,l}$	LCC_1	$EHP_{1,1}$	…	$EHP_{m,1}$
…							
m	$PC_{1,m}$	…	$PC_{l,m}$	LCC_m	$EHP_{1,n}$	…	$EHP_{l,m}$

At this stage, each maintenance alternative included in the decision matrix is screened to verify its compatibility with external constraints, in particular budget constraints that limit the costs incurred by the agency within a predetermined time interval on a specific section of the road network (see Equation 33)).

$$\sum_{t=t_0}^{t^*} C_{i,t} \leq B_{t^*} \tag{33}$$

Where:

$C_{i,t}$ is the cost incurred by the managing agency for the i-th maintenance alternative in each time interval t included in the analysis period t*;

B_{t^*} is the maximum budget available to the managing agency in the analysis period t* specifically targeted to maintain the road pavement section under analysis.

All the solutions that do not respect these constraint are excluded from the decision matrix.

Finally, each i-th maintenance alternative is assigned a synthetic score based on the utility method [123], equal to the sum of the products between the normalized value of the j-th indicator and the weight assigned to the j-th indicator (see Equation (34)).

$$U_i = \sum_j w_j \cdot n_{i,j} \tag{34}$$

Where:

U_i is the final score of the i-th alternative according to the utility method, w_j is the weight (importance) assigned to the j-th indicator and $n_{i,j}$ is the normalized value of the j-th indicator of the i-th maintenance alternative.

Before defining the weight vector for the MADM, the 22 criteria were collected into three sub-groups:

- The performance indicators at the end of the analysis period, namely FD, R and PCI (where available) make up the overall Pavement condition (PC);)
- The LCC indicator alone represented the costs incurred by the road managing agency in the analysis period (LCCA group);
- The 18 indicators obtained by LCA analysis (see Section 0) were collected to constitute the Environmental and human health performance of the asphalt mixtures (EHP).

The final weight vector was defined by distributing the weight evenly among each group. This choice was made because the environmental aspects are not always involved in the decisions concerning road pavements, that most of all focus on the mehanical features of the materials. Even in the latter case, basing the choice on a single performance indicator is not always satisfactory. Various degradations can occur and affect the bearing capacity of the pavement, eventually causing failure before the expected end of its useful life, if the choice is not carried out correctly. Therefore, it was decided to give the same weight to all groups of indicators to keep under control all these aspects that can be discriminating in the selection of a solution.

The weight assigned to each engineering performance group (PC, LCCA and EHP) was equally divided among all indicators; for the environmental group (EHP), as shown in Figure 10.

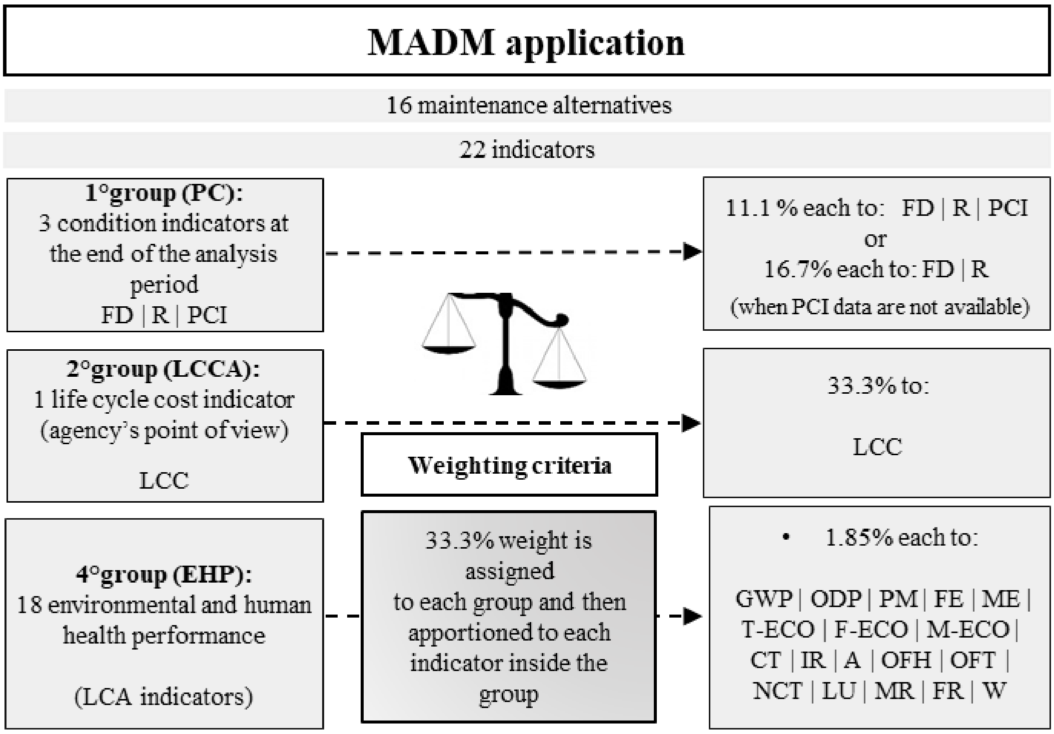


Figure 10 – Overview of MADM application and weighting criteria

A sensitivity analysis (see Figure 11) was carried out on the stability of the outcome of the MADM. Sensitivity analysis plays an important role in verifying the robustness of a study's conclusions [128]. In particular, the credibility of the results of a study increases if they remain consistent under different assumptions, methods or scenarios. If the results remain robust under different assumptions, methods or scenarios, this can strengthen their credibility. In order to carry out a sensitivity analysis, 24 different weight configurations were adopted in addition to the base weight configuration.

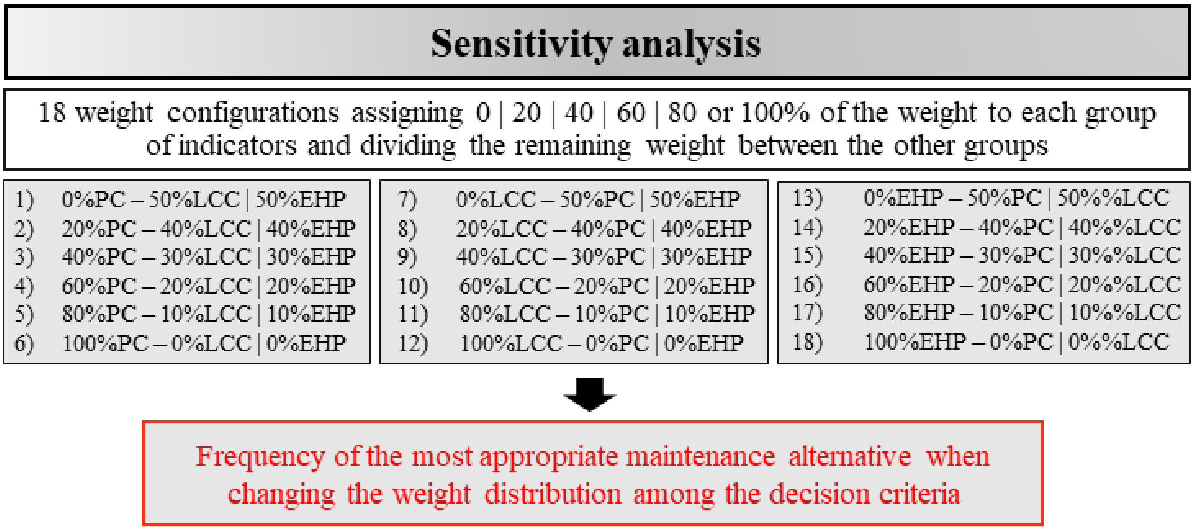


Figure 11 - Flow diagram of the sensitivity analysis

The weights of 0, 20, 40, 60, 80, and 100% were allocated each time to each group (PC, LCC and EHP), and the remaining weights, respectively of 100, 80, 60, 40, 20, and 0%, were split equally among the other groups. Inside each group, the assigned weight was split among the single indicators in the same way of the configuration 0.

Finally, the best alternative maintenance solution was found for each of the 18 weighting scenarios. To identify the most suitable solution taking into account the sensitivity analysis results, the frequency of appearance of the best maintenance alternative was calculated by using Equation (35).

$$f_n = \frac{m_n}{m} \tag{35}$$

Where:

- m_n is the number of times that the n-th maintenance alternative resulted as the best-compromise alternative considering the decision criteria;
- m is equal to the number of the analysis performed for the total weight configurations (18 plus the configuration 0).

7.10 Design of the Pavement Information Model

Taking into account the engineered maintenance algorithm, a visual programming tool (namely Dynamo, an open source Add-in for Autodesk and Revit applications) was leveraged to implement further sustainability and PMS-based analyses in a BIM project.

"Visual Programming Language" is a concept that provides designers with the necessary means to construct unique relationships between digital objects using a simple graphical user interface. Rather than coding from scratch, the user is able to assemble existing custom relationships by connecting pre-packaged nodes together to make a custom algorithm. The main consequence is that designers, who do not usually have developed coding skills, can implement computational concepts and enrich they projects with targeted calculations.

Dynamo allows designers to automate processes, perform data manipulation, implement relational structures, analytic capabilities and control Vasari Families and Parameters, which would not be usually possible without a conventional modelling interface. Last, but not least, Dynamo offers the designer the opportunity of doing so within the context of a BIM environment.

At this point, the BIM of the road pavement (Civil 3D [129]) was then fully informatized using a combination of visual scripting and Python scripting to retrieve the necessary information during each step of the PMS. Additional alphanumeric information were assigned to the digital 3D solids of the road pavement, in addition to the geometric features of the parametric pavement section extruded over the road alignment; these information were collected into property sets, namely custom sets of parameters associated to a certain object that can be easily accessed by the user in the Extended Data tab. Figure 12 shows a schematic representation of the Pavement Information Model.

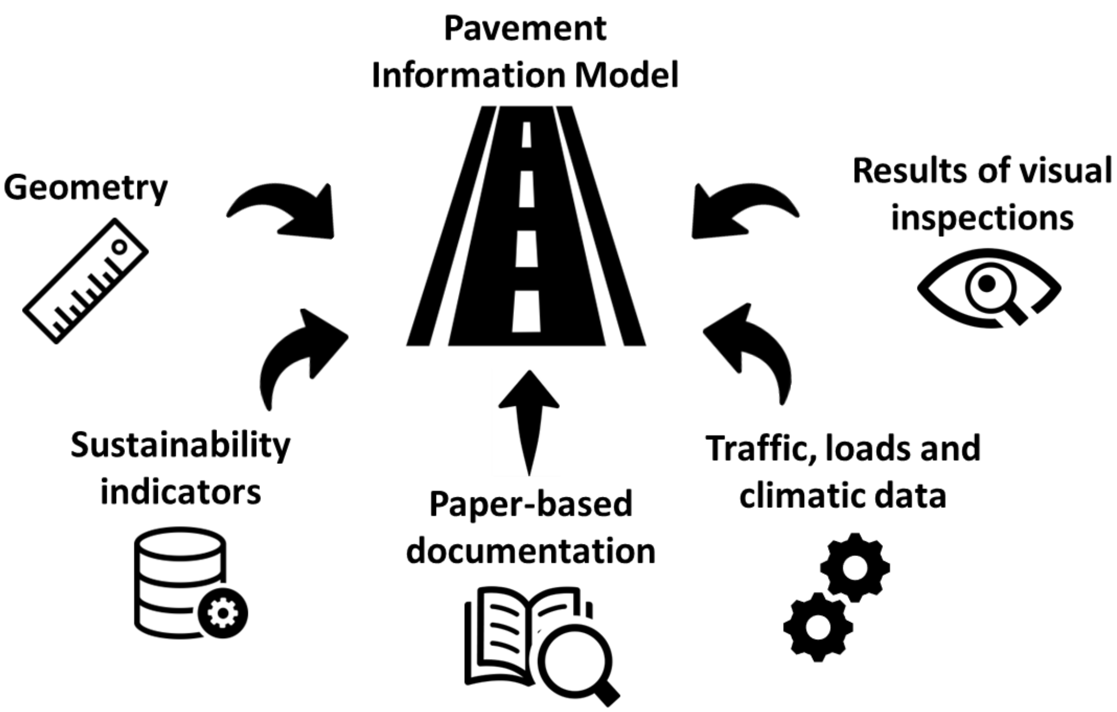


Figure 12 – Pavement Information Model design

Each property, belonging to a specific property set, can be regarded as:

- input property: its value is assigned directly from the data template imported by the user and does not require additional calculations;
- output property: its value is the result of the calculations of the analytic tools supporting the pavement BIM.

The following property sets were implemented into the BIM environment (see Figure 13):

- Pset_Pavement: the property set includes the current features of the asphalt pavement, such as the asphalt mixture identifiers of each layer and the coefficients of the PCI, FD and R decay curves;
- Pset_WearingCourse, Pset_BinderLayer, Pset_BaseLayer: the three input property sets, each one attached to the respective asphalt layer of the pavement structure, include all the necessary information that should be uploaded in the BIM environment before performing the LCA in absence of a specific EPD;

- Pset_MADM: the property set includes the input parameters that set up the boundary conditions for MADM (the weighting coefficients of each indicator and the maximum budget constraint in the analysis period).
- Pset_Maintenance: the property set includes both input (analysis period) and output parameters (type of maintenance strategy, number of years before next maintenance intervention, relative trigger condition, value of each condition indicator before next maintenance intervention) referred to the current pavement configuration.
- Pset_LCAindicators: the output property set includes the environmental impact categories that will be filled once ran the analysis tool on the current pavement configuration. In particular, Hierarchical ReCiPe midpoint impact assessment methodology [124] was chosen to address 18 different environmental problems through as many impact category indicators.
- Pset_LCCAindicators: the property set includes both input (discount rate) and output parameters (LCCA indicator, salvage value of the pavement at the end of the analysis period) used to characterize the life cycle cost dimension of the current pavement configuration.

Since the creation of property sets is time-consuming and could easily lead to errors in structuring the data, the command block embedded into Dynamo programming interface was leveraged to automate the creation and upload of the parameters into the BIM environment.

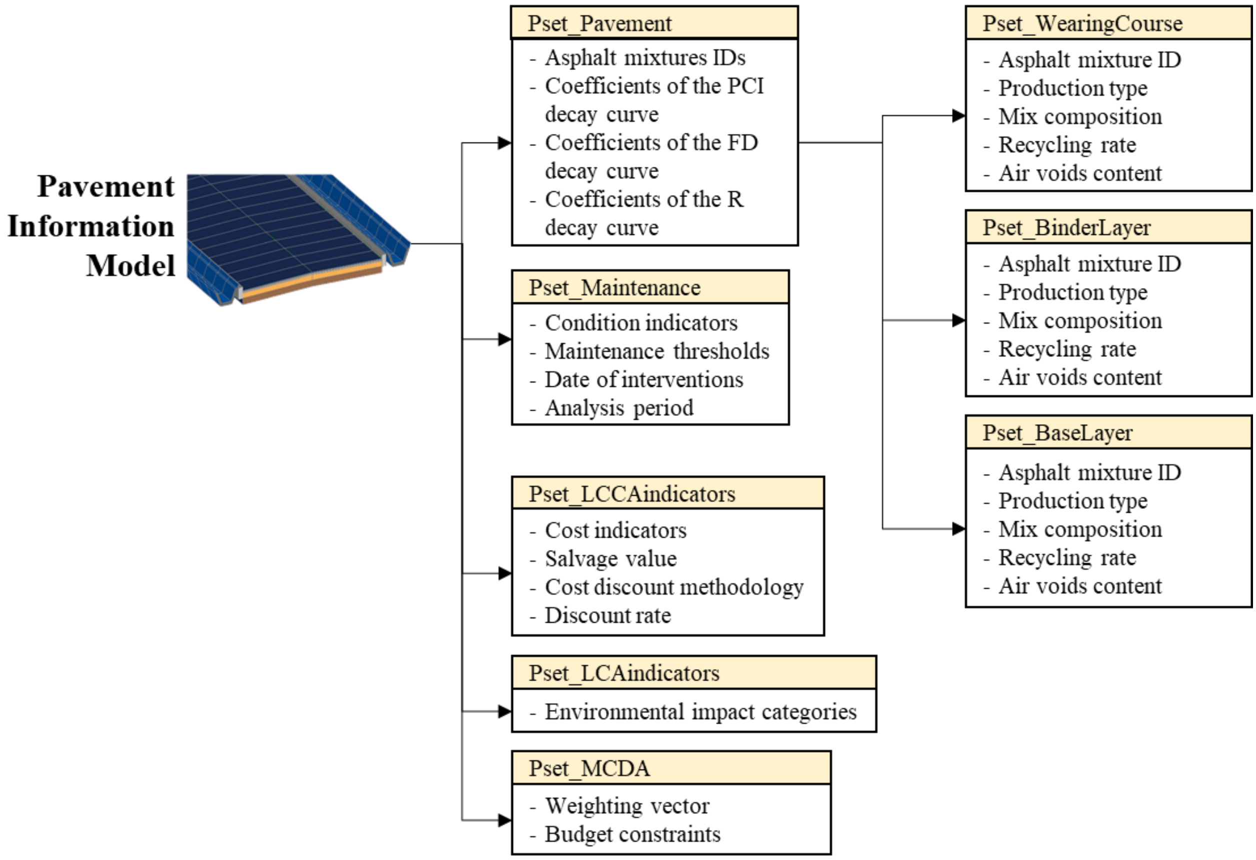


Figure 13 - Structure of the pavement information model and main properties included in each property set

7.11 Design of the analytic BIM-based tools

From the point of view of the integration of BIM, PMS and life cycle analyses, I used Dynamo, a Civil3D extension that creates a dynamic link between the BIM environment and an open-source visual programming environment and equipped the pavement BIM with additional analytic tools that run calculations and update the values of the object properties with the outputs of the calculations.

A schematic overview of the designed analytic tools is reported in Figure 14.

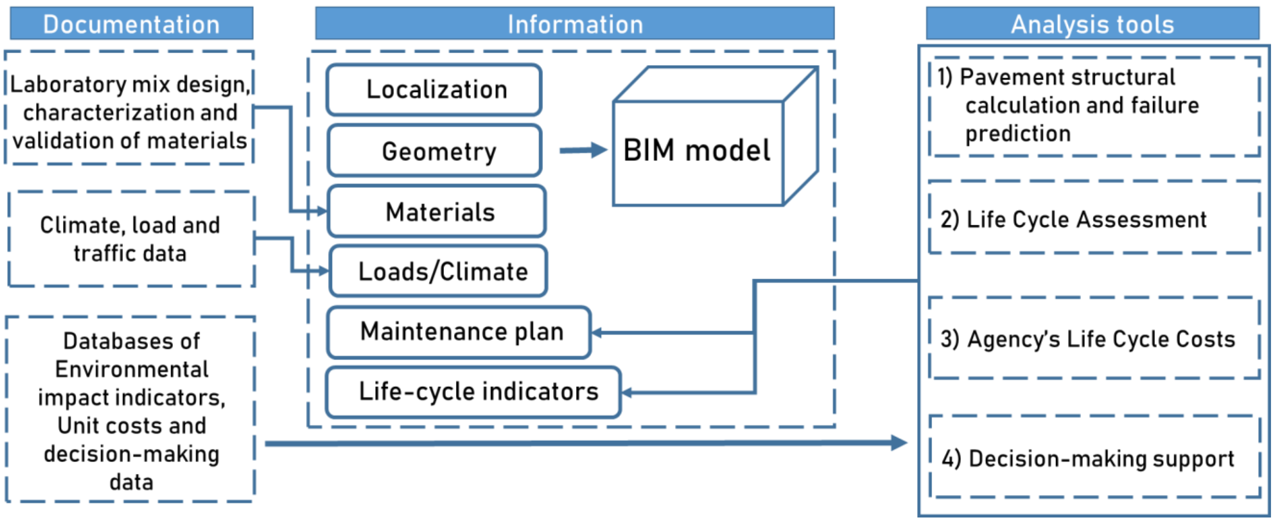


Figure 14 -Schematic overview of the components of the BIM analytic tools and data exchange path

The analytic tools (which are Dynamo files with .dyn extension) must be executed in series to produce the desired decision-making result and are as follows:

- The PMS tool gathers the information (time series of PCI surveys, predictive rutting and fatigue accumulations laws, pavement solutions library, intervention thresholds etc.) and calculates the type and timing of the maintenance interventions according to different maintenance approaches as seen in Sections 0 and 7.6;
- The LCA/LCCA tool gathers the outputs of the PMS tool, as well as the libraries of unit costs and impact category indicators for each stage of the expected life cycle of the pavement to calculate a set of life cycle indicators for each alterative pavement solutions;
- The MADM tool applies the budget constraints and performs the final decision-making basing on the decision matrix set up by the execution of the previous analysis tools. The MADM tool also updates the final values of the output properties, including the number of years before the next intervention, the condition indicator that triggers the need for maintenance, the cost and the environmental impact indicators of the life cycle of the optimal solution.

Figure 16 and Figure 17 shows respectively the visual programming script of LCCA, LCA and MADM tools as they appear in the Dynamo programming environment;

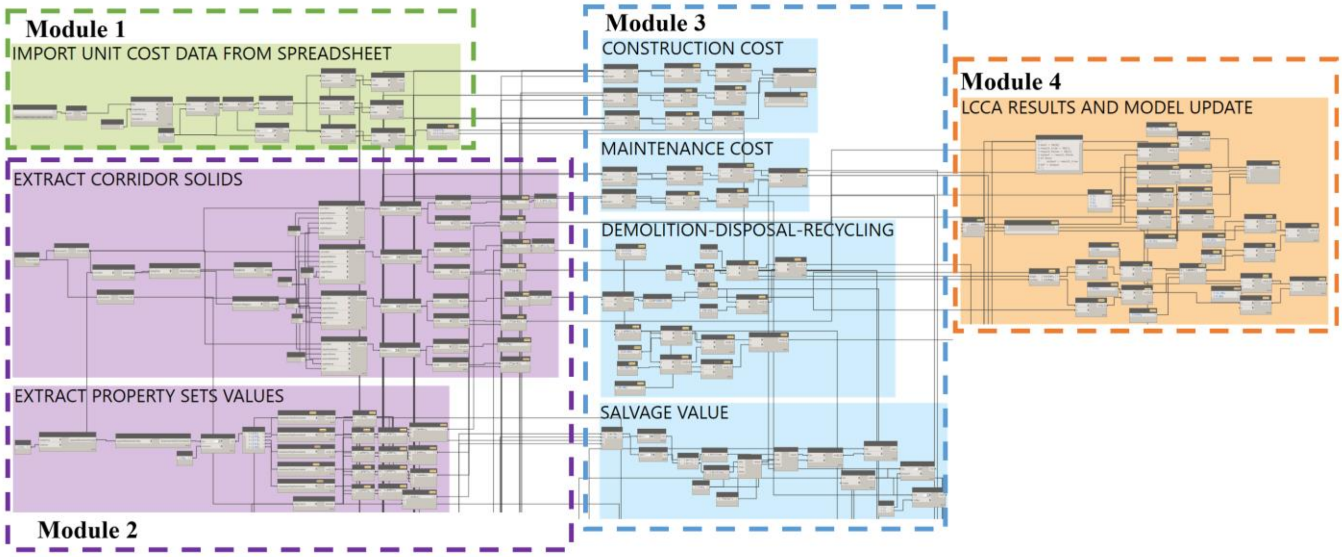


Figure 15 – Representation of the visual programming code for LCCA calculation as it appears in the Dynamo programming environment

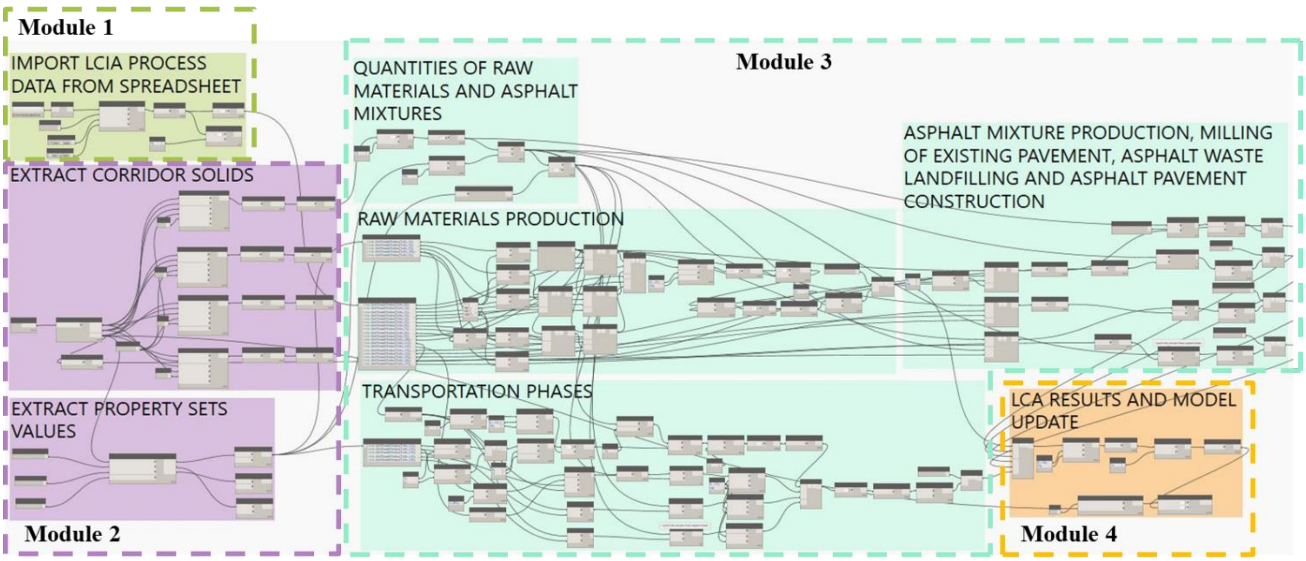


Figure 16 - Representation of the visual programming code for LCA calculation as it appears in the Dynamo programming environment

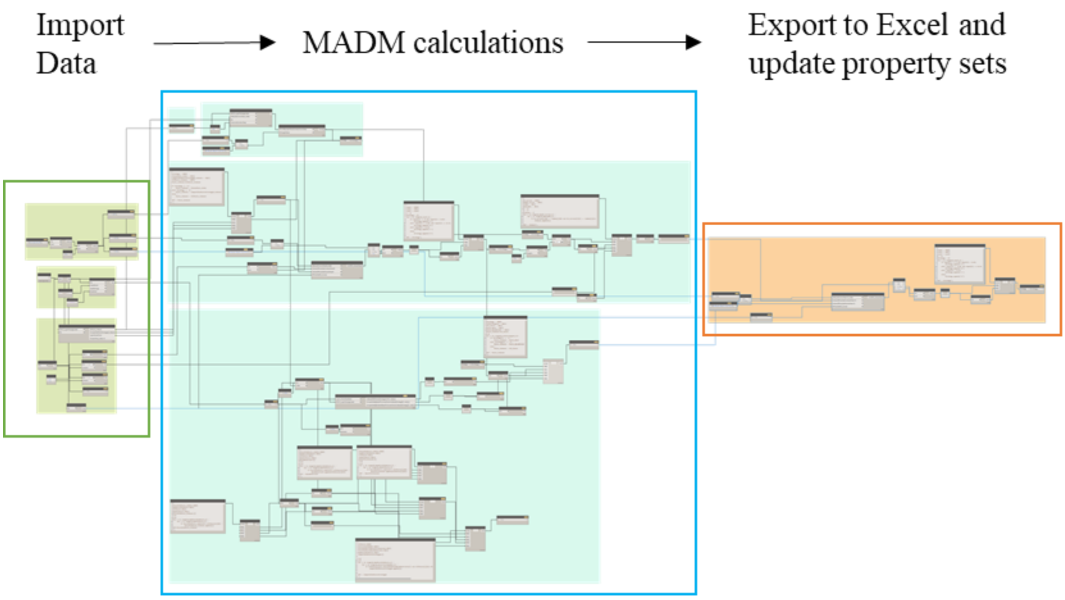


Figure 17 – Representation of the visual programming code for MADM as it appears in the Dynamo programming environment

Each module of the algorithm also includes the production of reports, exported as spreadsheets, like the time evolution of the condition indicators for each unit sample, and the timing, type, cost and environmental impacts of each maintenance strategy for each unit.

8 Results

Looking at the application to an illustrative case study, the described methodology was implemented to create a fully informatized BIM of a road pavement for which an historical series of monitoring data was available. First of all, the basic model was implemented with all the geometric information about the thicknesses of the asphalt layers, enabling the automation of materials' volumes and surface areas calculation. In the present work, the pavement geometry was reconstructed basing on the project documentation (i.e. coordinates of the road axis, width of the transverse sections, thickness of the pavement layers etc.).

After the conventional modelling phase, a visual programming tool associated with Autodesk calculation codes, which is Dynamo [130], was employed to support the pavement BIM with several analysis tools, designed through an hybrid of visual programming and Python scripting.

The elaborated procedure was applied and its effectiveness was tested in a real case study, in which BIM was used as a decision support system to choose the optimum maintenance intervention and draft future maintenance plans basing on the available life cycle and performance data at the time of the analysis.

The following Sections briefly show the results as they are obtained by feeding the information (collected into predetermined data templates) into the BIM environment and running the BIM analysis tools.

8.1 Pavement maintenance strategies

Considering the structure of the PMS reported in Chapter 7, the results here reported concern:

- A reactive maintenance strategy at year 0 based on the results of the visual survey of distresses in situ (see Figure 8 and Table 10);
- Two predictive strategies considering the time evolution of the condition indicators R, FD and PCI (where available) e the relative thresholds of the condition indicators triggering the maintenance intervention: a) a "reconstruction strategy" where the condition indicators are brought to the maximum decay before any structural intervention is carried out, and b) a "surface/deep rehabilitation strategy" where the wearing course and binder layer are milled and reconstructed more frequently to keep a high riding quality and preserve the deepest layers.

Looking firstly at the output of the reactive maintenance plan, the distress survey sheet reported in Table 10 was screened through the reactive maintenance algorithm to apply and overlap the trigger conditions shown in Figure 8.

The results as they are exported from the BIM environment to Excel are shown in Table 12. Table 12 is the first output of the BIM analysis tool, and shows the adopted intervention and the volume of materials useful to perform subsequent calculations. In the illustrative case study here adopted, the reactive maintenance strategy consists of an extraordinary maintenance intervention entailing the full reconstruction of the asphalt layers; despite the PCI value is above the threshold for both reconstruction and rehabilitation, the amount of pavement surface covered in visible fatigue cracking requires the demolition and reconstruction until the depth of the base layer, being the subbase and subgrade still in adequate service conditions.

Table 12 -BIM tool output for reactive maintenance strategy

Parameter	**Units**	**Value**
Type of reactive maintenance	-	Full reconstruction of the asphalt layers
Trigger condition	-	Extension of visible fatigue cracking
PCI value	-	56
Volume of asphalt sealants	m^3	0
Volume of asphalt mixture for the wearing course	m^3	Volume to be selected according to the design geometry
Volume of asphalt mixture for the binder layer	m^3	Volume to be selected according to the design geometry
Volume of asphalt mixture for the base layer	m^3	Volume to be selected according to the design geometry

The application of the predictive maintenance algorithm produced the number and sequence of future intervention years for each alternative maintenance strategy/asphalt materials. The sequence of intervention years and the triggering condition for each maintenance action performed across a 50 years period is shown in Table 13, which is also the second output of the BIM-based analysis tool.

Table 13 -BIM tool output for the predictive maintenance strategy

n°	**Type of approach**	**Pavement solution**	**Sequence of maintenance interventions (y)**	**Sequence of triggering conditions**
1	Reconstruction	HMA-HMA-HMA	0,18,36	PCI,FD,FD
2	Reconstruction	HMA-PMA-HMA	0,21,42	PCI,FD,FD
3	Reconstruction	HMA-HMMA-HMA	0,20,40	PCI,FD,FD
4	Reconstruction	HMA-HMAC-HMA	0,19,38	PCI,FD,FD
5	Reconstruction	HMA-HMA-CMRA	0,17,34	PCI,FD,FD
6	Reconstruction	HMA-PMA-CMRA	0,22,44	PCI,FD,FD
7	Reconstruction	HMA-HMMA-CMRA	0,20,40	PCI,FD,FD
8	Reconstruction	HMA-HMAC-CMRA	0,20,40	PCI,FD,FD
9	Reconstruction	HMA-HMA-HMAJ	0,24,48	PCI,FD,FD
10	Reconstruction	HMA-PMA-HMAJ	0,29	PCI,FD
11	Reconstruction	HMA-HMMA-HMAJ	0,26	PCI,FD
12	Reconstruction	HMA-HMAC-HMAJ	0,25,50	PCI,FD,FD
13	Rehabilitation	HMA-HMA	7,14,21,28,35,42,49	PCI,PCI,PCI,PCI,PCI,PCI,PCI
14	Rehabilitation	HMA-PMA	13,26,39	R,R,R,R
15	Rehabilitation	HMA-HMMA	15,30,45	R,R,R
16	Rehabilitation	HMA-HMAC	9,18,27,36,45	R,R,R,R,R

8.2 Life cycle assessment results

The life cycle assessment observes and analyses a product or service over its entire life cycle in order to determine its environmental impacts. The LCA methodology is a systematic set of procedures for compiling and examining the inputs and outputs of materials, energy, waste, pollutant emissions (LCI) and the associated environmental impacts (LCIA) directly attributable to the functioning of a product or service system throughout the unit processes of its life cycle. In LCA, a unit process is defined as the "smallest element considered in the life cycle inventory analysis for which input and output flows are quantified" (ISO 14040).

First, the motivation behind the study was to compare, under homogeneous hypotheses and system conditions, different sustainable construction/maintenance solutions involving the use of waste and recycled modification polymers combined in the binder and base layers of road pavements and find out which pavement configurations has the lower environmental impacts in terms of conservation of the natural environment and resources.

In order to do so, the 12 reconstruction alternatives were assumed as alternative maintenance solutions for the same case study, which involved the demolition and reconstruction of the wearing course, binder, and base layers of an existing pavement on a 1-km section of a single-carriageway road (width equal to 10.5 m) located in southern Italy. The main processes included in the system boundary that refer to each construction/maintenance intervention and the relative distances between the local facilities involved in the analysis are reported in Figure 18.

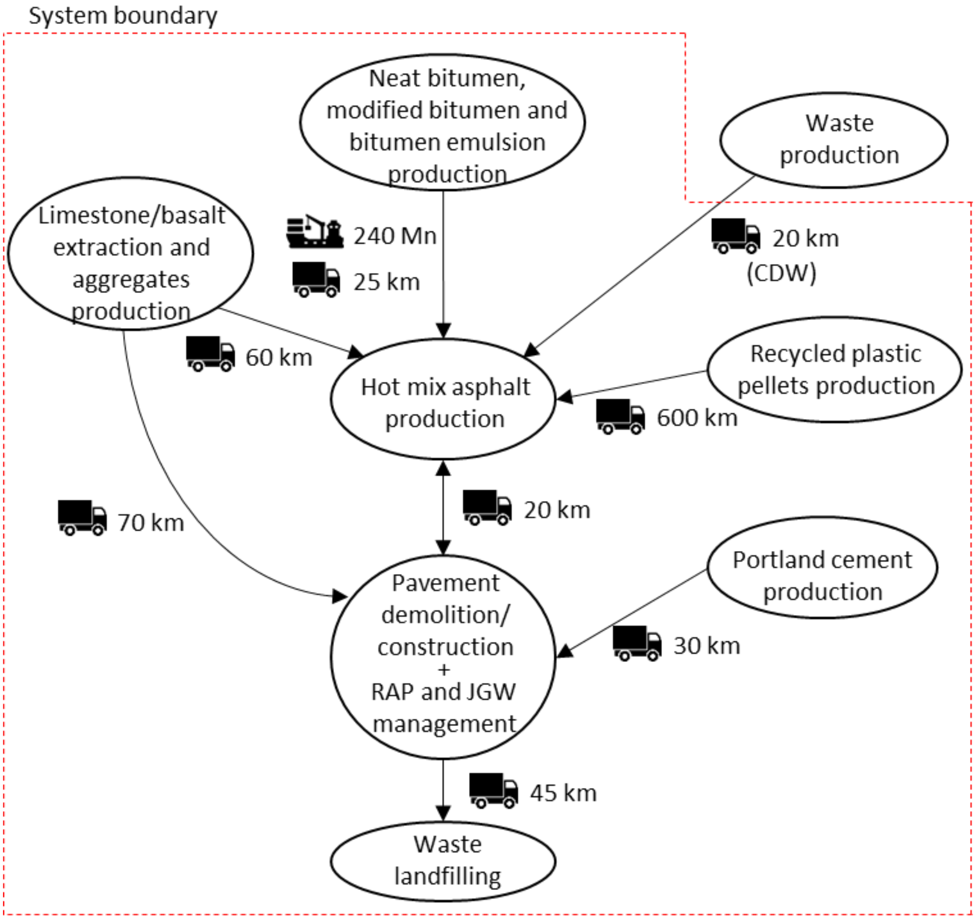


Figure 18 - Overview of the facilities involved in the system boundary (considering all the possible phases of the life cycle) and relative transportation distances of the case study.

8.2.1 System Description and Data Collection

The LCI phase involves the collection of primary and secondary data for the modelling of the flows that stream trough the unit processes of the system, namely input flows, such as materials and fossil fuels (crude oil, natural gas, and coal), and output flows, such as waste and pollutant emissions to air (CO_2, CO, CH_4, NO_x, SO_2, NH_3, polycyclic aromatic hydrocarbons (PAH), non-methane volative organic compounds (NMVOC), and particulate matter) and water (chemical oxygen demand (COD), biological oxygen demand (BOD5), and nitrogen and sulfur compounds).

The following subsections give a description of the unit processes involved in each phase of the life cycle and the relative data sources used to compile the LCI.

A complete overview of the data sources gathered for LCA is summarised in Table 14,Table 15 andTable 16.

Table 14 -Overview of the data sources for Life Cycle Assessment – part 1

Phase of the life cycle	Unit process	Primary data	Year of survey	Secondary data
Aggregates production	coarse limestone aggregates coarse basalt aggregates limestone sand limestone filler	Amount in the asphalt mixtures	2019/ 2020	Ecoinvent 3 database: Gravel, crushed {RoW}| production | Cut-off, U Ecoinvent 3 database: Basalt {RER}| quarry operation | Cut-off, U Ecoinvent 3 database: Sand {RoW}| gravel and quarry operation | Cut-off, U Ecoinvent 3 database: Lime, packed {Europe without Switzerland}| lime production, milled, packed | Cut-off, U
Bituminous binders production	neat bitumen SBS-modified bitumen bitumen emulsion	Amount in the asphalt mixtures	2019/ 2020	The Eurobitume Life-Cycle Inventory for Bitumen, Version 3.1, European Bitumen Association, Brussels, Belgium (2020)
Cement production	cement production	Amount in the cold asphalt mixtures	2019/ 2020	Ecoinvent 3 database: Cement, Portland {Europe without Switzerland}| market for | Cut-off, U
Recycled polymer pellets production	Plastic waste recycling and shredding Pelletisation	Amount in the asphalt mixture	2019/ 2020	Ecoinvent 3 database: Polyethylene terephthalate, granulate, bottle grade, recycled {RoW}| polyethylene terephthalate production, granulate, bottle grade, recycled | Cut-off, U Santos et al. (2021)
CDW management	Waste concrete treatment facility	Amount in the asphalt mixture	2019/ 2020	Ecoinvent 3: Waste concrete gravel {RoW}| treatment of waste concrete gravel, recycling | Cut-off, U
JGW management	JGW collection	Amount of JGW produced in the construction site (210 t) Productivity of the shovel (24.8 m^3/h)	2019	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Crushing of JGW)
	JGW crushing	Amount in the asphalt mixtures Productivity of the jaw mill (150 t/h)	2019/ 2020	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Crushing of JGW)
RAP management	RAP collection	Amount of RAP produced in the construction site (210 t)	2019	Ecoinvent 3: Waste asphalt {RoW}| treatment of, sanitary landfill | Cut-off, U

Table 15 - Overview of the data sources for Life Cycle Assessment – part 2

Phase of the life cycle	Unit process	Primary data	Year of survey	Secondary data
Hot mix asphalt production	Asphalt plant infrastructure			Ecoinvent 3 database: Industrial machine, heavy, unspecified {GLO}| market for | Cut-off, U
	Wheel loader for aggregates moving	Amount of aggregates in the hot mix asphalt Productivity of the wheel loader (70 t/h)	2019/ 2020	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U
	Convey aggregates to the drum dryer	Amount of aggregates in the hot mix asphalt	2019/ 2020	Ecoinvent 3 database: Conveyor belt {GLO}| market for | Cut-off, U
	Aggregates drying	Amount of asphalt mixture Unit natural gas consumption (8.79 m^3/t of asphalt mix)	2019/ 2020	Ecoinvent 3 database: Drying, natural gas {GLO}| market for | Cut-off, U
	Asphalt mixing	Amount of asphalt mixture. Unit electricity consumption = 4.37 kWh/t of asphalt mix	2019/ 2020	Ecoinvent 3 database: Electricity, medium voltage {IT}| market for | Cut-off, U United States Environmental Protection Agency: emissions of Benzo(a)pyrene = 4.66E-10 kg/t United States Environmental Protection Agency: emissions of NMVOC = 0.00019 kg/t
Pavement construction with hot mix asphalt	Laying of hot mix asphalt	Amount of asphalt mixture productivity of machinery = 351 t/h (wearing course), 205 t/h (binder layer), 117 t/h (base layer)	2021	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Paver)
	Compaction of hot mix asphalt			Ecoinvent 3 database: Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Roller)
Base layer construction with cold in-place recycling technique	Surface levelling and RAP placing over the pavement surface	Amount of cold asphalt mixture Grader productivity = 545 m^2/h	2019/ 2020	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Grader)
	Mixing of components and laying of cold mix asphalt	Pulvimixer productivity = 750m^2/h	2021	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Pulvimixer)
	Compaction of cold mix asphalt	3 rollers, productivity = 141 t/h	2021	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Roller 1) Ecoinvent 3 database: Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Roller 2) Ecoinvent 3 database: Machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Roller 3)

Table 16 - Overview of the data sources for Life Cycle Assessment – part 3

Phase of the life cycle	Unit process	Primary data	Year of survey	Secondary data
End of life	Demolition of the pavement	Productivity of the milling machine = 150 t/h	2020	Ecoinvent 3 database: Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| market for | Cut-off, U (Milling machine)
	Disposal in landfill	Amount of landfilled asphalt waste	2019	Ecoinvent 3 database: Waste asphalt {RoW}| treatment of, sanitary landfill | Cut-off, U
Transportation	Transport by ship	Covered distance. Amount of materials (raw materials, asphalt mixtures, asphalt waste) to be supplied	2019/ 2020	Ecoinvent 3 database: Transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas {GLO}| market for transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas | Cut-off, U
	Transport by road		2019/ 2020	Ecoinvent 3 database: Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U

8.2.1.1 Natural Aggregates Production

This phase involves the operations of rock mining, transportation of raw rocks to the aggregates production plant, the crushing and sieving phase, the loading of the aggregates into the trucks, and the transportation of aggregates either to the asphalt plant, for hot asphalt production, or to the construction site, for the granulometric correction of RAP's aggregate size distribution in cold in-place recycling operations. In particular, two different types of coarse aggregates were considered: Limestone aggregates, included in the mix design of the binder and base layer asphalt mixtures, and basalt aggregates, which are usually used in the wearing course due to high abrasion and crushing resistance. Instead, natural sand and filler always had a calcareous origin. The inventory data for the production on 1 kg of coarse limestone and basaltic aggregates were gathered from the Ecoinvent 3 database [131] and referred to the amount of aggregates in each asphalt mixture (see Table 4 andTable 5).

8.2.1.2 Management and Supply of CDW, JGW and RAP

As already mentioned in Section 7.1, the CDW was supplied from an external facility, so the inventory flows associated with their treatments and transportation phases were computed only when the analyzed pavement configuration involved the reuse of these secondary materials in the binder layer (HMAC).

On the other hand, the RAP and the JGW originated from the construction site under analysis (7098 and 210 t, respectively), therefore their management operations either corresponded to disposal (for the pavement configurations with HMA base layer) or partial/total recycling (for HMAJ and CMRA base layers).

All the inventory flows of the crushing (mobile diesel-powered jaw mill with a productivity of 150 t/h) and transportation phases (trucks with capacity of 20 t travelling the distances reported in Figure 18) were selected from the Ecoinvent 3 database and referred to the amount of waste reused in substitution of natural aggregates (see Table 4 andTable 5).

8.2.1.3 Bituminous Binders Production and Supply

The production of petroleum derivatives takes place within the refinery, where the extracted crude oil is distilled into several products: The heaviest fraction is the neat bitumen. In the present analysis, the neat bitumen is used to bind the aggregates of several hot asphalt mixtures for the wearing course

(HMA) binder (HMA, HMAC, and PMA) and base layer (HMA and HMAJ) that make up the corresponding asphalt pavement configurations. Instead, HMMA and the cold mixture for the base layer (CMRA) required SBS-modified bitumen and bitumen emulsion, respectively. Both the modified bitumen and the bitumen emulsion were obtained from the high shear milling of the neat bitumen with SBS-polymers or hot water, respectively. After that, the binders were hauled to the asphalt plant (see Figure 18). The inventory data for the production on 1 kg of neat bitumen, modified bitumen, and bitumen emulsion were gathered from the European Bitumen Association [132] and referred to the binder content of each asphalt mixture (see Table 4 andTable 5).

8.2.1.4 Cement Production and Supply

The manufacturing of Portland cement involves the burning of a mixture of crushed rocks in a kiln, and the grinding of the burned product, known as clinker, together with a small percentage of gypsum. The cold mixture of the base layer (CMRA) required Portland cement (according to the percentage reported in Table 5) to speed up the breakage of bitumen emulsion and to strengthen the final mixture. For that reason, Portland cement was hauled directly to the construction site for cold-in place recycling operations. The inventory data for the production of 1 kg of Portland cement were found in the Ecoinvent 3 database.

8.2.1.5 Recycled Polymer Pellets Production

The conversion of waste plastic into recycled pellets for asphalt dry modification (PMA) mainly involves the processes of waste collection, sorting, shredding, and pelletization (in which plastic shreds are heated up to 190 °C and extruded to become pellets). In the present work, the inventory data were gathered both from the Ecoinvent 3 database (for the collection, sorting, and shredding of waste plastics) and from Santos et al. [133] for the electricity and water consumption and the waste generation during the pelletization process. The amount of polymer pellets that make up PMA is reported in Table 4.

8.2.1.6 Hot Mix Asphalt Production

All the hot asphalt mixtures for the wearing course (HMA), binder (HMA, HMAC, HMMA and PMA), and base layer (HMA and HMAJ) were produced in a batch plant at a high temperature (160–180 °C). Some of the useful data used to quantify the inventory flows were surveyed at a local asphalt plant:

- The productivity of a wheel loader that handles the aggregates from the stockpiles to the plant supply system, equal to 60 m^3/h and powered by diesel fuel;
- the natural gas consumption, equal to 8.79 m^3 for each tonne of asphalt mixture, required for drying the aggregates in the drum dryer, and;
- the electricity consumption of the asphalt plant, equal to 4.37 kWh/t of asphalt mixture, that powers the high-temperature storage and feeding system of bitumen and the mixing of aggregates, filler, and bitumen for the production of the hot asphalt mixture.

All the input and output inventory flows were then selected for the corresponding operations from the Ecoinvent 3 database. In addition, the emissions to air of 16 mg/kg of NMVOC, 40 mg/kg of PM10, and 2 mg/kg of PM2.5 were considered during hot asphalt mixture production, as reported in tier 2 emission factors by the United States Environmental Protection Agency [134] for the batch hot asphalt mixing plant setup with a pollutant abatement system. The amount of hot asphalt mixtures produced at the asphalt plant was estimated based on the thickness of each layer (see Table 8).

8.2.1.7 Pavement Construction

Road pavement construction operations differ for hot in-plant produced and cold in-place recycled asphalt mixtures in terms of the machinery involved for the laying and compaction to reach the desired density.

Looking at the construction operations with hot asphalt, the paving and the roller machines work in series to place the asphalt on the surface and compact it. The survey of actual paving operations allowed estimating the productivity of the whole construction for each pavement layer (351 t/h for the wearing course, 205 t/h for the binder, and 117 t/h for the base layer). The type and power and the machinery helped in selecting the list of unit inventory flows from the Ecoinvent 3 database.

The CMRA base layer, instead, is mixed and laid during cold in-place recycling operations. Cold in-place recycling involves:

- The operation of a diesel-powered motor grader, which places the milled RAP back on the subbase surface with a productivity of 1815 m^2/h of road surface;
- the mixing of RAP (and eventually JGW), natural aggregates, cement, water, and bitumen emulsion (each one of them supplied by trucks and tankers to the construction site) by a diesel-powered pulvimixer, which works 750 m^2/h of pavement surface; and;

- the compaction of the placed cold mixture up to the desired density reached during the mix design, involving two large pneumatic tire rollers and a large vibratory steel wheel roller, all of them with a productivity of 141 t/h.

8.2.1.8 Demolition and Disposal to Landfill

Lastly, each asphalt pavement stratigraphy, once reaching the end of the service life (reported in Table 8), is demolished (through a milling machine with a productivity of 150 t/h), hauled to the nearest disposal site, and landfilled. As a matter of fact, the recyclability potential of the analyzed asphalt mixtures made up of waste and secondary raw materials should be further assessed. The inventory flows arising from asphalt waste landfilling were estimated from the specific section of the Ecoinvent 3 database.

8.2.1.9 Manteinance

According to each maintenance program resulting from the PMS, the maintenance phase required the supplying of raw materials, the pavement demolition and reconstruction operations and partial or total landfilling of asphalt waste; the specific inventory data selected for the maintenance operations are, for each process, the same as those reported in the previous Sections.

8.2.1.10 Transportation Phases

The transportation of the raw materials, semi-finished products, and waste, according to the scheme reported in Figure 18, was carried out by road through heavy vehicles, specifically dump and tank trucks, whose emissions and resources consumption were estimated from the Ecoinvent 3 database. Additionally, the bituminous binders were also transported from the respective production facilities to the asphalt plant by sea into freighters. Freight transportation data were, again, gathered from Ecoinvent 3 database.

8.2.2 Life Cycle Impact Assessment

The LCIA phase, as stated in the international guidelines of ISO 14044, consists of converting the input and output flows of the LCI into synthethic impact category indicators, addressed as understandable and quantifiable measures of specific environmental problems that affect the human health, the environment and the availability of natural resources. In this study, the impact assessment of the designed pavement solutions was performed through SimaPro 9® software. Among the impact assessment models available in the literature, the Egalitarian ReCiPe [124] impact assessment method was selected both for its diffusion in the construction sector and for the number of environmental problems quantified by its impact category indicators, namely 18 midpoint indicators and 3 endpoint indicators. Midpoint and endpoint level indicators refer to different phases in the cause–effect chain that starts from the inventory flows, converted into midpoint effects on specific environmental topics which, at the end of the cause–effect chain, produce effects on broader endpoint impact categories, such as human health, ecosystems, and resource availability. The following midpoint impact categories were assessed:

- Global warming potential (GWP, kg CO_2 eq), which quantifies the integrated infrared radiative forcing increase of a greenhouse gas (GHG), expressed in kg CO2-eq;
- Stratospheric ozone depletion (ODP, kg CFC11 eq) refers to a time-integrated decrease in stratospheric ozone concentration over an infinite time horizon;
- Ionizing radiation (IR, kBq Co-60 eq) measures the equivalent amount of radionuclides that are released into the atmosphere during the nuclear fuel cycle and other activities such as the burning of coal. Long-live radionuclides eventually contaminate the food chain and/or drinking waters where their ionizing radiation causes damage to human health;
- Damage of ozone formation on terrestrial ecosystems (OFT, kg NO_x eq) relates to the sum of the differences between the hourly mean ozone concentration and 40 ppb during daylight hours over the relevant growing season;
- Damage of ozone formation on human health (OFH, kg NO_x eq) measures the human population intake of ozone derived from the emission of a precursor (nitrogen oxides (NO_x) or non-methane volatile organic compounds (NMVOC));
- Fine particulate matter formation (PM, kg PM2.5 eq) represents the human population intake of PM2.5 resulting from the emission of a precursor, i.e. NH_3, NO_x, SO_2 and primary PM2.5;
- Terrestrial acidification (A, kg SO_2 eq) refers to the change in acidity in the soil due to a change in acid deposition due to air emission of NO_x, NH_3 and SO_2;
- Freshwater eutrophication (FE, kg P eq) indicates the amount of phosphorus forms into freshwaters;
- Marine eutrophication (ME, kg N eq) indicates the amount of nitrogen forms into marine ecosystems;

- Terrestrial, freshwater and marine ecotoxicity (T-ECO, F-ECO and M-ECO, kg 1,4-DCB eq) represent the impact of pollutants on the probability distribution function of species due to a change in the environmental concentration of a chemical
- Human carcinogenic and non-carcinogenic toxicity (CT and NCT, kg 1,4-DCB eq). These indicators reflect the change in lifetime disease incidence, both in the form of cancerous and non-cancerous diseases, linked to a change in terms of intake of the substance;
- Land use (LU, m^2 a crop eq) refer to the relative species loss caused by a specific land use type (annual crops, permanent crops, mosaic agriculture, forestry, urban land, pasture);
- Mineral resource scarcity (MR, kg Cu eq) expresses the average extra amount of ore produced in the future caused by the extraction of a mineral resource considering all future production of that mineral resource;
- Fossil resource scarcity (FR, kg oil eq) is defined as the ratio between the higher heating value of a fossil resource and the energy content of crude oil;
- Water consumption (W, m^3) refers to the volume in m^3 of water consumed per m^3 of water extracted.

Once modelled all the phases of the life cycle and gathered all the environmental impact indicators for each of those phases, the data template reported in Table 17 and Table 18 was imported in the programming environment; then, the LCA calculation tool combines the LCIA input data and the results of the PMS analysis tools according to Equation (19) up to Equation (23).

The LCA results as obtained from the BIM analysis tool are reported in Table 19.

In detail, four indicators, namely the GWP, PM, FECO and FR, present the highest variations among the alternatives and therefore have been reported in Figure 19a, 19b, 19c and 19d, respectively. Concerning the GWP, the combination of a polymer modified asphalt mixture for the base layer with a cold in-place recycled base layer lowers the GWP by 35% compared to that of the traditional reconstruction solution with HMA; the reason is the combination of using high rate of recycled materials in the base layer, which lowers the overall amount of greenhouse gases emissions (e.g. CO_2, CH_4, NMVOC) from both industrial facilities and transportation of virgin raw materials to the asphalt plant, and the satisfactory performance in terms of FD and R accumulation, as well as the service life of the designed pavement. On the other hand, the traditional rehabilitation strategy with HMA both in the binder and wearing course does not provide with satisfactory results in terms of GWP (+33% compared to the traditional reconstruction strategy with HMA); the underlying reason is the high frequency of maintenance interventions to keep the R condition index under the predeterminate threshold of 20 mm depth, which entail high consumption of virgin resources, fossil fuels and energy.

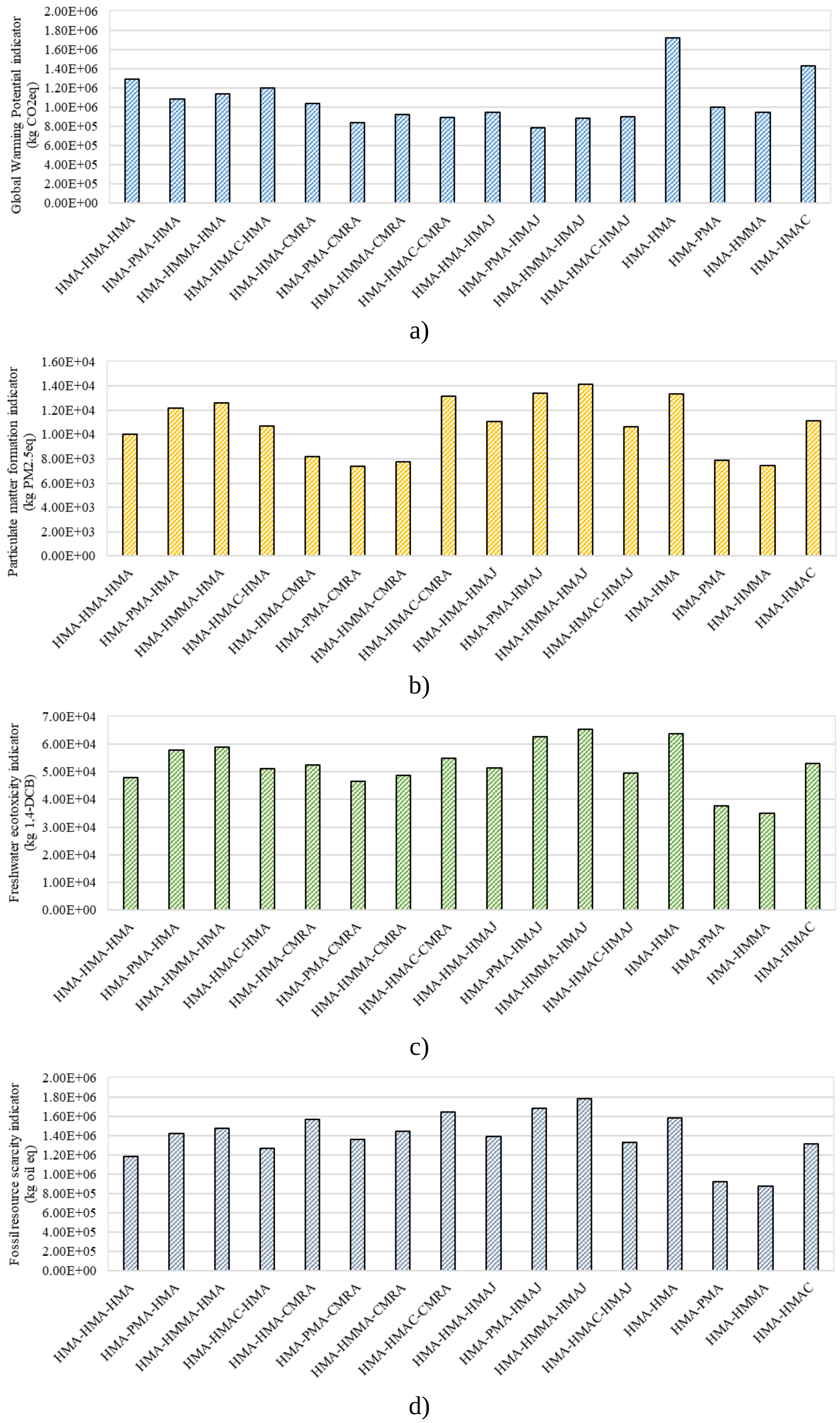


Figure 19 – LCA results for: a) global warming potential indicator, b) particulate matter formation indicator, c) freshwater ecotoxicity indicator and d) fossil resource scarcity indicator

Table 17 – Data template of LCIA indicators specific for each process of the life cycle – part 1

	GWP	ODP	IR	OF-H	PM	OF-T	A	FE	ME	T-ECO	F-ECO	M-ECO	CT	NCT	LU	MR	FR	W
Processes	kg CO2 eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg PM2.5 eq	kg NOx eq	kg SO2 eq	kg P eq	kg N eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m2a crop eq	kg Cu eq	kg oil eq	m3
Production of Limestone Aggregates (1 t)	8.52E+00	1.60E-15	1.55E+00	3.00E-02	1.94E-02	3.06E-02	3.59E-02	5.25E-03	3.60E-04	2.39E+01	5.40E-01	7.05E-01	7.75E-01	1.15E+01	4.81E-01	1.13E-01	2.27E+00	3.76E-01
Production of Basalt Aggregates (1 t)	6.96E+00	1.20E-15	1.38E+00	7.89E-02	2.78E-02	8.03E-02	5.16E-02	2.83E-03	2.38E-04	1.06E+01	2.16E-01	2.87E-01	2.55E-01	5.19E+00	5.96E+00	1.62E-02	2.04E+00	5.36E-02
Production Limestone Sand (1 t)	4.16E+00	1.52E-15	2.76E-01	2.27E-02	9.84E-03	2.31E-02	1.85E-02	1.45E-03	1.00E-04	1.15E+01	2.17E-01	2.82E-01	2.89E-01	4.15E+00	3.78E-01	3.28E-02	1.10E+00	1.41E+00
Production Basalt Sand (1 t)	4.16E+00	1.30E-15	2.76E-01	2.27E-02	9.84E-03	2.31E-02	1.85E-02	1.45E-03	1.00E-04	1.15E+01	2.17E-01	2.82E-01	2.89E-01	4.15E+00	3.78E-01	3.28E-02	1.10E+00	1.41E+00
Production Limestone Filler (1 t)	4.58E+01	2.00E-14	7.69E+00	1.27E-01	7.99E-02	1.29E-01	1.59E-01	2.00E-02	8.46E-03	8.41E+01	1.59E+00	2.12E+00	1.87E+00	4.58E+01	1.48E+01	8.06E-02	8.07E+00	1.43E+00
Production of Alternative Filler (1t)	4.58E+01	1.40E-14	7.69E+00	1.27E-01	7.99E-02	1.29E-01	1.59E-01	2.00E-02	8.46E-03	8.41E+01	1.59E+00	2.12E+00	1.87E+00	4.58E+01	1.48E+01	8.06E-02	8.07E+00	1.43E+00
Production of Neat Bitumen (1 t)	2.08E+02	1.53E-13	0.00E+00	1.31E+00	4.07E-01	1.36E+00	1.38E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+03	1.11E+00
Production of PMB (1 t)	3.87E+02	3.56E-13	0.00E+00	1.81E+00	6.96E-01	1.85E+00	2.37E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E+03	8.13E+00
Production of Bitumen Emulsion (1 t)	1.83E+02	2.12E-13	0.00E+00	8.32E-01	2.73E-01	8.61E-01	9.27E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.90E+02	1.35E+00

Table 18 - Data template of LCIA indicators specific for each process of the life cycle – part 2

Processes	GWP kg CO2 eq	ODP kg CFC11 eq	IR kBq Co-60 eq	OF-H kg NOx eq	PM kg PM2.5 eq	OF-T kg NOx eq	A kg SO2 eq	FE kg P eq	ME kg N eq	T-ECO kg 1,4-DCB	F-ECO kg 1,4-DCB	M-ECO kg 1,4-DCB	CT kg 1,4-DCB	NCT kg 1,4-DCB	LU m2a crop eq	MR kg Cu eq	FR kg oil eq	W m3
Production of Portland Cement (1 t)	8.57E+02	4.28E-13	2.60E+01	1.34E+00	4.40E-01	1.35E+00	1.25E+00	8.97E-02	5.93E-03	5.50E+02	8.45E+00	1.11E+01	7.66E+00	1.84E+02	5.10E+00	4.81E+00	6.61E+01	1.99E+00
Tap Water supply (1t)	3.43E-01	2.83E-16	1.09E-01	8.23E-04	6.09E-04	8.47E-04	1.36E-03	2.53E-04	0.00E+00	1.03E+00	1.80E-02	2.44E-02	1.17E-01	4.67E-01	1.12E-02	4.57E-03	9.03E-02	1.01E+00
Road transportation (1 tkm)	1.65E-01	1.89E-16	3.84E-03	7.57E-04	2.06E-04	7.72E-04	4.91E-04	0.00E+00	0.00E+00	2.97E+00	3.89E-03	6.67E-03	3.48E-03	1.22E-01	7.08E-03	6.35E-04	5.71E-02	2.65E-04
Transportation by sea (1 tkm)	7.52E-03	2.46E-17	0.00E+00	1.35E-04	0.00E+00	1.36E-04	1.43E-04	0.00E+00	0.00E+00	2.04E-02	0.00E+00	1.25E-04	1.81E-04	1.43E-03	0.00E+00	0.00E+00	2.22E-03	0.00E+00
Production of HMA (1 t)	2.90E+00	5.70E-14	2.47E-01	4.15E-02	3.44E-03	6.26E-02	9.45E-03	6.38E-04	0.00E+00	3.55E+00	6.92E-02	9.08E-02	1.12E-01	1.45E+00	6.44E-02	6.82E-03	8.72E-01	3.21E-02
Construction of HMA pavement (1 t)	2.43E+00	5.11E-14	2.77E-02	1.65E-02	4.03E-01	1.84E-02	7.27E-03	0.00E+00	0.00E+00	2.93E+00	1.55E-02	2.22E-02	4.96E-02	3.26E-01	5.80E-03	4.04E-03	7.68E-01	1.72E-03
Cold in-place recycling (1 m2	4.03E-01	7.12E-16	4.58E-03	1.95E-03	4.42E-04	1.98E-03	1.10E-03	0.00E+00	0.00E+00	4.85E-01	2.56E-03	3.67E-03	8.06E-03	5.34E-02	9.60E-04	6.69E-04	1.27E-01	2.84E-04
Demolition of asphalt pavement (1 t)	1.02E+00	2.67E-16	1.16E-02	5.78E-03	1.22E-03	5.87E-03	3.07E-03	0.00E+00	0.00E+00	1.22E+00	6.46E-03	9.25E-03	2.07E-02	1.36E-01	2.42E-03	1.69E-03	3.21E-01	7.17E-04
Landfilling of asphalt waste (1 t)	1.82E+01	5.37E-13	3.77E-01	8.30E-02	2.65E-02	8.47E-02	5.68E-02	1.67E-03	7.82E-02	3.62E+01	1.26E+00	1.72E+00	5.33E-01	1.13E+01	2.90E+00	4.30E-02	5.76E+00	2.61E-01
Recycling of RAP (1 t)	1.75E-01	2.52E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Recycling of CDW (1 t)	2.16E+00	5.07E-16	9.21E-02	7.56E-03	3.28E-03	7.69E-03	6.16E-03	4.84E-04	3.34E-05	3.83E+00	7.22E-02	9.39E-02	9.64E-02	1.38E+00	1.26E-01	1.09E-02	3.68E-01	4.70E-01
Production of polymer pellets for mix modication (1 t)	4.87E+02	1.88E-13	0.00E+00	1.61E+00	5.01E-01	1.67E+00	1.70E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E+03	1.37E+00

Table 19 – LCA results as obtained from the BIM analysis tool

Environmental impact indicator	Units	HMA-HMA-HMA	HMA-PMA-HMA	HMA-HMMA-HMA	HMA-HMAC-HMA	HMA-HMA-CMRA	HMA-PMA-CMRA	HMA-HMMA-CMRA	HMA-HMAC-CMRA	HMA-HMA-HMAJ	HMA-PMA-HMAJ	HMA-HMMA-HMAJ	HMA-HMAC-HMAJ	HMA-HMA	HMA-PMA	HMA-HMMA	HMA-HMAC
GWP	kg CO2 eq	1.29E+06	5.33E-01	5.68E+04	6.78E+03	1.00E+04	7.38E+03	4.79E+03	1.76E+02	1.59E+03	1.02E+07	4.78E+04	6.87E+04	3.57E+04	8.34E+05	1.15E+05	4.50E+03
ODP	kg CFC11 eq	1.08E+06	6.28E-01	6.87E+04	8.03E+03	1.21E+04	8.75E+03	5.70E+03	2.14E+02	1.94E+03	1.15E+07	5.78E+04	8.27E+04	4.29E+04	9.95E+05	1.38E+05	5.33E+03
IR	kBq Co-60 eq	1.14E+06	6.44E-01	7.01E+04	8.33E+03	1.26E+04	9.07E+03	5.97E+03	2.18E+02	2.00E+03	1.18E+07	5.88E+04	8.42E+04	4.37E+04	1.01E+06	1.42E+05	5.44E+03
OFH	kg NOx eq	1.20E+06	5.70E-01	6.07E+04	7.26E+03	1.07E+04	7.89E+03	5.12E+03	1.89E+02	1.70E+03	1.09E+07	5.11E+04	7.35E+04	3.82E+04	8.92E+05	1.23E+05	4.81E+03
PM	kg PM2.5 eq	1.04E+06	5.87E-01	6.57E+04	7.63E+03	8.18E+03	8.13E+03	5.77E+03	2.04E+02	1.76E+03	1.02E+07	5.23E+04	7.47E+04	3.87E+04	9.02E+05	1.34E+05	5.50E+03
OFT	kg NOx eq	8.36E+05	5.12E-01	5.39E+04	6.74E+03	7.37E+03	7.18E+03	5.03E+03	1.62E+02	1.56E+03	9.17E+06	4.65E+04	6.65E+04	3.36E+04	7.96E+05	1.19E+05	4.86E+03
A	kg SO2 eq	9.25E+05	5.46E-01	6.01E+04	7.16E+03	7.73E+03	7.62E+03	5.51E+03	1.91E+02	1.63E+03	9.53E+06	4.86E+04	6.94E+04	3.61E+04	8.41E+05	1.24E+05	5.08E+03
FE	kg P eq	8.96E+05	5.97E-01	6.21E+04	8.01E+03	8.59E+03	8.53E+03	6.06E+03	2.14E+02	1.85E+03	1.07E+07	5.49E+04	7.84E+04	4.06E+04	9.48E+05	1.41E+05	5.77E+03
ME	kg N eq	9.44E+05	5.60E-01	6.00E+04	7.37E+03	1.11E+04	8.03E+03	5.25E+03	1.87E+02	1.76E+03	1.04E+07	5.14E+04	7.36E+04	3.80E+04	8.75E+05	1.22E+05	4.75E+03
TECO	kg 1,4-DCB	7.87E+05	6.77E-01	7.25E+04	8.90E+03	1.34E+04	9.70E+03	6.35E+03	2.28E+02	2.13E+03	1.25E+07	6.27E+04	8.97E+04	4.61E+04	1.07E+06	1.47E+05	5.75E+03
FECO	kg 1,4-DCB	8.81E+05	7.10E-01	7.60E+04	9.43E+03	1.41E+04	1.03E+04	6.81E+03	2.37E+02	2.24E+03	1.31E+07	6.52E+04	9.33E+04	4.82E+04	1.11E+06	1.55E+05	6.02E+03
MECO	kg 1,4-DCB	8.99E+05	5.39E-01	5.76E+04	7.08E+03	1.06E+04	7.71E+03	5.04E+03	1.80E+02	1.69E+03	9.96E+06	4.94E+04	7.07E+04	3.65E+04	8.41E+05	1.17E+05	4.56E+03
CT	kg 1,4-DCB	1.72E+06	7.10E-01	7.57E+04	9.04E+03	1.34E+04	9.83E+03	6.38E+03	2.35E+02	2.12E+03	1.36E+07	6.37E+04	9.16E+04	4.76E+04	1.11E+06	1.53E+05	5.99E+03
NCT	kg 1,4-DCB	9.97E+05	4.11E-01	4.47E+04	5.25E+03	7.89E+03	5.71E+03	3.72E+03	1.39E+02	1.26E+03	7.63E+06	3.76E+04	5.38E+04	2.79E+04	6.49E+05	8.98E+04	3.48E+03
LU	m2a crop eq	9.47E+05	3.86E-01	4.18E+04	4.97E+03	7.46E+03	5.41E+03	3.55E+03	1.30E+02	1.19E+03	7.18E+06	3.51E+04	5.03E+04	2.61E+04	6.04E+05	8.46E+04	3.26E+03
MR	kg Cu eq	1.43E+06	5.90E-01	6.29E+04	7.51E+03	1.11E+04	8.17E+03	5.31E+03	1.95E+02	1.76E+03	1.13E+07	5.29E+04	7.61E+04	3.96E+04	9.24E+05	1.27E+05	4.98E+03
FR	kg oil eq	1.29E+06	5.33E-01	5.68E+04	6.78E+03	1.00E+04	7.38E+03	4.79E+03	1.76E+02	1.59E+03	1.02E+07	4.78E+04	6.87E+04	3.57E+04	8.34E+05	1.15E+05	4.50E+03
W	m3	1.08E+06	6.28E-01	6.87E+04	8.03E+03	1.21E+04	8.75E+03	5.70E+03	2.14E+02	1.94E+03	1.15E+07	5.78E+04	8.27E+04	4.29E+04	9.95E+05	1.38E+05	5.33E+03

8.3 Agency's life cycle costs

The calculation of the LCCA indicator for the construction and maintenance operations of the asphalt layers of a flexible road pavement was implemented as a visual script within Dynamo software, being able to dynamically interact and exchange information regarding, among others, the chosen design solution, in terms of layers thicknesses and main features of the asphalt materials, and the volumes of materials needed for the specific road works.

To calculate the construction and maintenance costs, it was necessary to calculate firstly the new prices for the unit cost of the asphalt materials included in the library of road asphalt pavement solutions, taking into account the different production and construction technologies for the asphalt layer solutions, as well as the direct costs associated to the unit prices of virgin and recycled materials, labour and equipment.

The calculation of the unit prices was implemented with a programming script in the Dynamo software with the following data, collected in different spreadsheets and imported in the programming environment, as input:

- mixture composition, as reported in the Table 4 and Table 5;
- type and working hours of the equipment necessary for the construction of the layers, according to the specific production and construction technology (e.g. dry modification of the mixture, cold in-place recycling technology);
- workers employed for the construction of the pavement layers, in terms of number of skilled workers and working hours needed for the driving and handling of the machinery;
- unit costs of materials, equipment and labour.

The data collection for the calculation of the unit prices of the asphalt materials was carried out by analysing the market prices of several local companies producing limestone and basaltic aggregates and asphalt mixtures, as well as companies carrying out road works that have already experimented the cold in-place recycling technology procedures, other than the consultation of up to date price lists of regional public works.

Therefore, the average unit costs collected for the materials, equipment and labour under analysis are summarized in Table 20, Table 21 and Table 22, respectively:

Table 20 – Average unit costs for materials

Material	Unit	Cost
Limestone 10/31.5 mm	€/t	17.00
Limestone 6/12 mm	€/t	17.00
Limestone 3/6 mm	€/t	17.00
Basalt 10/16 mm	€/t	21.00
Basalt 5/10 mm	€/t	21.00
Basalt 3/6 mm	€/t	21.00
Limestone Sand	€/t	17.00
Limestone Filler	€/t	21.00
Bitumen 50/70	€/t	358.86
Bitumen Emulsion	€/t	550.00
SBS Modified Bitumen 10/40-70	€/t	460.00
Polymer	€/t	1700.00
Cement	€/t	111.62
RAP	€/t	0.00
JGW	€/t	0.00
Water	€/t	1.37

Table 21 - Average unit costs for equipment

Equipment	Function	Unit	Cost
Sprinkler	• application of a bituminous emulsion between an existing asphalt surface and a newly constructed bituminous overlay • spraying water to enhance workability of cold mixtures	€/h	59.20
Truck (steady phase)	transport of raw aggregates, RAP and other raw materials during the cold in-place recycling operations (speed is very low or 0)	€/h	62.87
Truck (go phase)	• transport of raw materials in the construction/asphalt production site • transport of waste to landfill	€/h-Km	2.00
Hot asphalt production plant	production of hot mixtures of bitumen and virgin or recycled aggregates	€/h	12.00
Roller	compaction of hot and cold asphalt layers until desired density	€/h	73.62
Paver	spreading and laying of hot asphalt mixtures for the construction of asphalt layers	€/h	128.20
Grader	leveling, evening and smoothing the subbase surface before paving	€/h	79.96
Pulvimixer	cold in-site recycling: screening, RAP sizing, addition of bituminous emulsion, cement, aggregates and water, mixing	€/h	75.92

Table 22 - Average unit costs for labour

Labour	**Skills**	**Unit**	**Cost**
Common	requires mostly physical skills associated with none or little technical knowledge, eventually achievable in a few days	€/h	27.75
Qualified	capable to perform jobs that require normal but specific technical capacity for their execution	€/h	30.80
Skilled*	capable of performing particular jobs that need special technical and practical competence, resulting from internship or from technical-practical preparation	€/h	33.20

To evaluate the economic feasibility for the alternatives designed, new prices of innovative materials have been calculated; the results in terms of unit costs for the production and supply of asphalt materials are reported in Table 23.

Table 23 - Unit costs for the production and supply of asphalt mixtures

Pavement layer	**Mixture ID**	**Unit**	**Price**
Wearing	HMA	€/t	106.40
Binder	HMA	€/t	98.52
	HMAC	€/t	95.74
	HMMA	€/t	104.13
	PMA	€/t	105.43
Base	HMA	€/t	93.74
	HMAJ	€/t	96.44
	CMRA	€/t	61.51

The results of the life cycle costs borne by the managing agency are reported in Table 24, with reference to cost items related to the manufacturing, construction and maintenance process of the bituminous solutions; in detail, both the LCC indicator without considering the salvage value of the pavement and the net LCC indicator are reported in the output datasheet generated by the BIM analysis tool.

Table 24 – Results of LCCA as obtained from the BIM analysis tool

n°	Type of approach	Pavement solution	LCC without considering the salvage value	Salvage value	LCC indicator
1	Reconstruction	HMA-HMA-HMA	1,394,143.7 €	36,570.5 €	1,357,573.2 €
2	Reconstruction	HMA-PMA-HMA	1,279,211.7 €	98,897.1 €	1,180,314.6 €
3	Reconstruction	HMA-HMMA-HMA	1,300,240.7 €	79,719.6 €	1,220,521.1 €
4	Reconstruction	HMA-HMAC-HMA	1,307,867.5 €	57,985.6 €	1,249,881.8 €
5	Reconstruction	HMA-HMA-CMRA	1,025,674.8 €	6,982.3 €	1,018,692.5 €
6	Reconstruction	HMA-PMA-CMRA	946,954.2 €	87,554.5 €	859,399.6 €
7	Reconstruction	HMA-HMMA-CMRA	979,180.1 €	60,034.9 €	919,145.1 €
8	Reconstruction	HMA-HMAC-CMRA	962,464.6 €	59,010.1 €	903,454.5 €
9	Reconstruction	HMA-HMA-HMAJ	902,280.9 €	108,807.7 €	793,473.1 €
10	Reconstruction	HMA-PMA-HMAJ	751,723.5 €	33,210.3 €	718,513.2 €
11	Reconstruction	HMA-HMMA-HMAJ	770,452.4 €	9,236.1 €	761,216.3 €
12	Reconstruction	HMA-HMAC-HMAJ	882,517.6 €	118,020.2 €	764,497.4 €
13	Rehabilitation	HMA-HMA	1,357,055.4 €	36,758.5 €	1,320,296.9 €
14	Rehabilitation	HMA-PMA	1,011,163.0 €	6,597.7 €	1,004,565.4 €
15	Rehabilitation	HMA-HMMA	981,135.2 €	28,589.9 €	952,545.2 €
16	Rehabilitation	HMA-HMAC	1,175,187.7 €	19,060.0 €	1,156,127.8 €

Additionally, by combining the sequence of maintenance actions and the NPV of each maintenance intervention, a time versus costs graph can be obtained, as reported in Figure 20.

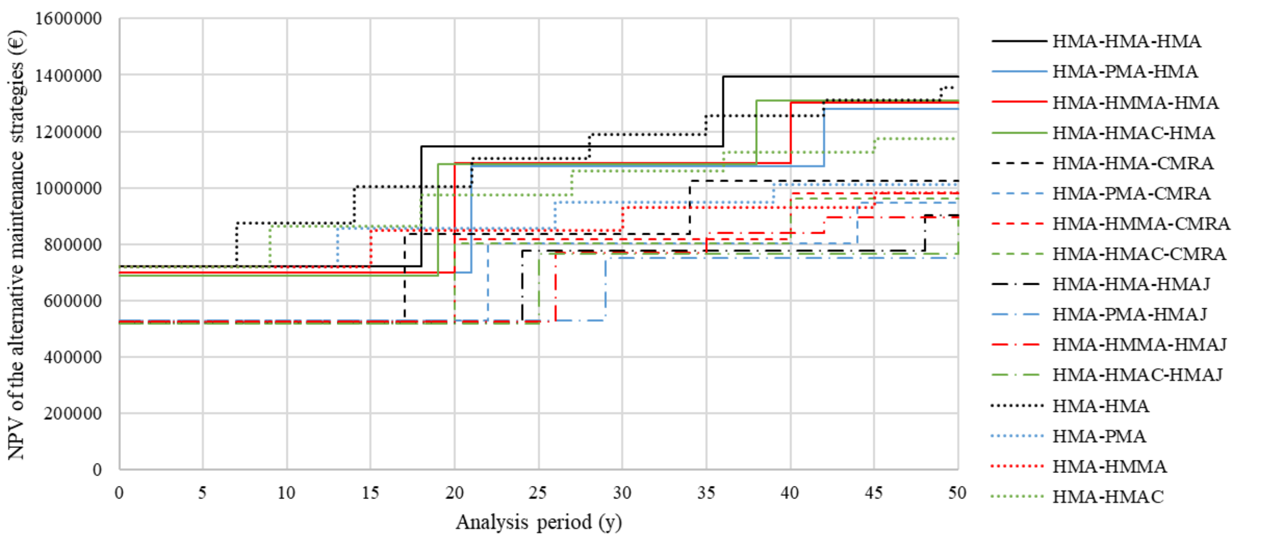


Figure 20 – Time vs. NPV of the maintenance alternatives

8.4 Trade-offs between the alternatives

MADM was here applied to support the decision maker with numerous and conflicting assessments, allowing for a compromise solution to be obtained in a transparent manner. To support the MADM to determine the robustness of evaluations by examining how much of the results can be influenced by changes in methods, models, values of unmeasured variables or hypotheses a sensitivity analysis is adopted.

In the present research four different alternatives have been designed, each one better than the other with respect to a specific dimension: for example the solutions with CRMA as a base layer are better than the others in terms of environmental dimension and costs of construction, but can be outperformed by stiffer solutions like HMAJ when it comes to the maintenance phase. To keep into account all the dimensions for the choice by decision-maker of “the best” solution between the range of feasible solutions to adopt across a 50 y analysis period, MADM has been adopted as comparative evaluation method.

The decision matrix that describes the set of alternatives and the relative value of the decision criteria is reported in Table 25, while the normalized decision matrix is shown in Table 26.

Table 25 – Decision matrix

Pavement solution	Units	HMA-HMA-HMA	HMA-PMA-HMA	HMA-HMMA-HMA	HMA-HMAC-HMA	HMA-HMA-CMRA	HMA-PMA-CMRA	HMA-HMMA-CMRA	HMA-HMAC-CMRA	HMA-HMA-HMAJ	HMA-PMA-HMAJ	HMA-HMMA-HMAJ	HMA-HMAC-HMAJ	HMA-HMA	HMA-PMA	HMA-HMMA	HMA-HMAC
R	mm	21.1966	1.3608	1.9282	16.1826	12.305	0.6884	0.5841	0.1748	1.521	0.7635	18.12	22	15.645	16.12	5.01	13.01
FD	-	0.81	0.56	0.51	0.46	0.82	0.1495	0.2916	0.27	0.4496	0.1634	0.8301	1	0.7288	0.11	0.07	0.16
PCI	-	60	-	-	-	-	-	-	-	-	-	-	-	59	-	-	-
GWP	kg CO2 eq	1.29E+06	1.08E+06	1.14E+06	1.20E+06	1.04E+06	8.36E+05	9.25E+05	8.96E+05	9.44E+05	7.87E+05	8.81E+05	8.99E+05	1720274.6	997273.89	946543.18	1429456.904
ODP	kg CFC11 eq	5.33E-01	6.28E-01	6.44E-01	5.70E-01	5.87E-01	5.12E-01	5.46E-01	5.97E-01	5.60E-01	6.77E-01	7.10E-01	5.39E-01	0.7101022	0.4105362	0.3857556	0.590057207
IR	kBq Co-60 eq	5.68E+04	6.87E+04	7.01E+04	6.07E+04	6.57E+04	5.39E+04	6.01E+04	6.21E+04	6.00E+04	7.25E+04	7.60E+04	5.76E+04	75675.815	44665.822	41776.632	62882.58657
OFH	kg NOx eq	6.78E+03	8.03E+03	8.33E+03	7.26E+03	7.63E+03	6.74E+03	7.16E+03	8.01E+03	7.37E+03	8.90E+03	9.43E+03	7.08E+03	9040.5165	5246.2448	4969.3242	7512.189479
PM	kg PM2.5 eq	1.00E+04	1.21E+04	1.26E+04	1.07E+04	8.18E+03	7.37E+03	7.73E+03	8.59E+03	1.11E+04	1.34E+04	1.41E+04	1.06E+04	13353.14	7891.0948	7459.1971	11095.7511
OFT	kg NOx eq	7.38E+03	8.75E+03	9.07E+03	7.89E+03	8.13E+03	7.18E+03	7.62E+03	8.53E+03	8.03E+03	9.70E+03	1.03E+04	7.71E+03	9831.1039	5712.7273	5409.4291	8169.125589
A	kg SO2 eq	4.79E+03	5.70E+03	5.97E+03	5.12E+03	5.77E+03	5.03E+03	5.51E+03	6.06E+03	5.25E+03	6.35E+03	6.81E+03	5.04E+03	6384.6896	3718.5306	3547.6046	5305.338253
FE	kg P eq	1.76E+02	2.14E+02	2.18E+02	1.89E+02	2.04E+02	1.62E+02	1.91E+02	2.14E+02	1.87E+02	2.28E+02	2.37E+02	1.80E+02	235.26383	139.32198	129.83593	195.4917581
ME	kg N eq	1.59E+03	1.94E+03	2.00E+03	1.70E+03	1.76E+03	1.56E+03	1.63E+03	1.85E+03	1.76E+03	2.13E+03	2.24E+03	1.69E+03	2119.8758	1257.2609	1186.8151	1761.50429
TECO	kg 1,4-DCB	1.02E+07	1.15E+07	1.18E+07	1.09E+07	1.02E+07	9.17E+06	9.53E+06	1.07E+07	1.04E+07	1.25E+07	1.31E+07	9.96E+06	13639255	7629157.9	7176554.7	11333497.43
FECO	kg 1,4-DCB	4.78E+04	5.78E+04	5.88E+04	5.11E+04	5.23E+04	4.65E+04	4.86E+04	5.49E+04	5.14E+04	6.27E+04	6.52E+04	4.94E+04	63718.874	37597.928	35074.833	52947.00289
MECO	kg 1,4-DCB	6.87E+04	8.27E+04	8.42E+04	7.35E+04	7.47E+04	6.65E+04	6.94E+04	7.84E+04	7.36E+04	8.97E+04	9.33E+04	7.07E+04	91619.692	53834.425	50264.811	76131.10186
CT	kg 1,4-DCB	3.57E+04	4.29E+04	4.37E+04	3.82E+04	3.87E+04	3.36E+04	3.61E+04	4.06E+04	3.80E+04	4.61E+04	4.82E+04	3.65E+04	47597.65	27949.231	26110.942	39551.12114
NCT	kg 1,4-DCB	8.34E+05	9.95E+05	1.01E+06	8.92E+05	9.02E+05	7.96E+05	8.41E+05	9.48E+05	8.75E+05	1.07E+06	1.11E+06	8.41E+05	1111894.5	649004.63	603694.77	923925.3599
LU	m2a crop eq	1.15E+05	1.38E+05	1.42E+05	1.23E+05	1.34E+05	1.19E+05	1.24E+05	1.41E+05	1.22E+05	1.47E+05	1.55E+05	1.17E+05	153100.19	89815.339	84626.625	127218.1357
MR	kg Cu eq	4.50E+03	5.33E+03	5.44E+03	4.81E+03	5.50E+03	4.86E+03	5.08E+03	5.77E+03	4.75E+03	5.75E+03	6.02E+03	4.56E+03	5994.1223	3482.6536	3257.7976	4980.79752
FR	kg oil eq	1.19E+06	1.42E+06	1.48E+06	1.27E+06	1.56E+06	1.36E+06	1.45E+06	1.64E+06	1.39E+06	1.68E+06	1.78E+06	1.33E+06	1580071	925835.96	877974.78	1312955.113
W	m3	2.06E+04	2.52E+04	2.67E+04	2.20E+04	2.31E+04	2.04E+04	2.25E+04	2.43E+04	2.22E+04	2.68E+04	2.91E+04	2.13E+04	27468.742	16324.641	15686.942	22825.06678
LCC indicator	€	1.36E+06	1.18E+06	1.22E+06	1.25E+06	1.02E+06	8.59E+05	9.19E+05	9.03E+05	7.93E+05	7.19E+05	7.61E+05	7.64E+05	1320296.9	1004565.4	952545.23	1156127.76

Table 26 - Normalized decision matrix

Decision criteria	HMA-HMA-HMA	HMA-PMA-HMA	HMA-HMMA-HMA	HMA-HMAC-HMA	HMA-HMA-CMRA	HMA-PMA-CMRA	HMA-HMMA-CMRA	HMA-HMAC-CMRA	HMA-HMA-HMAJ	HMA-PMA-HMAJ	HMA-HMMA-HMAJ	HMA-HMAC-HMAJ	HMA-HMA	HMA-PMA	HMA-HMMA	HMA-HMAC
R	0.0005	0.0073	0.0052	0.0006	0.0008	0.0145	0.0171	0.0572	0.0066	0.0131	0.0006	1.0000	0.0006	0.0006	0.0020	0.0008
FD	0.0123	0.0179	0.0196	0.0217	0.0122	0.0669	0.0343	0.0370	0.0222	0.0612	0.0120	1.0000	0.0137	0.0909	0.1429	0.0625
PCI	1.0000	-	-	-	-	-	-	-	-	-	-	-	0.9833	-	-	-
GWP	0.6101	0.7290	0.6917	0.6562	0.7573	0.9414	0.8514	0.8791	0.8337	1.0000	0.8932	0.8761	0.4577	0.7894	0.8317	0.5508
ODP	0.7242	0.6147	0.5994	0.6768	0.6572	0.7537	0.7072	0.6462	0.6883	0.5696	0.5435	0.7162	0.5432	0.9396	1.0000	0.6538
IR	0.7359	0.6081	0.5956	0.6878	0.6360	0.7745	0.6951	0.6727	0.6965	0.5761	0.5500	0.7248	0.5520	0.9353	1.0000	0.6644
OFH	0.7327	0.6190	0.5966	0.6848	0.6510	0.7374	0.6944	0.6200	0.6741	0.5581	0.5268	0.7019	0.5497	0.9472	1.0000	0.6615
PM	0.7353	0.6067	0.5855	0.6872	0.9005	1.0000	0.9529	0.8576	0.6653	0.5505	0.5216	0.6929	0.5516	0.9334	0.9875	0.6638
OFT	0.7335	0.6185	0.5964	0.6855	0.6658	0.7530	0.7102	0.6341	0.6737	0.5577	0.5268	0.7015	0.5502	0.9469	1.0000	0.6622
A	0.7407	0.6228	0.5941	0.6922	0.6145	0.7048	0.6443	0.5852	0.6758	0.5583	0.5211	0.7038	0.5556	0.9540	1.0000	0.6687
FE	0.7357	0.6053	0.5957	0.6875	0.6368	0.8002	0.6805	0.6064	0.6928	0.5703	0.5468	0.7210	0.5519	0.9319	1.0000	0.6642
ME	0.7463	0.6129	0.5924	0.6975	0.6753	0.7624	0.7303	0.6431	0.6731	0.5570	0.5291	0.7012	0.5599	0.9440	1.0000	0.6738
TECO	0.7014	0.6218	0.6072	0.6555	0.7031	0.7827	0.7534	0.6696	0.6932	0.5750	0.5492	0.7207	0.5262	0.9407	1.0000	0.6332
FECO	0.7338	0.6066	0.5963	0.6858	0.6707	0.7536	0.7224	0.6387	0.6827	0.5591	0.5381	0.7107	0.5505	0.9329	1.0000	0.6625
MECO	0.7313	0.6079	0.5971	0.6835	0.6730	0.7561	0.7247	0.6410	0.6833	0.5602	0.5388	0.7113	0.5486	0.9337	1.0000	0.6602
CT	0.7313	0.6084	0.5971	0.6834	0.6745	0.7769	0.7239	0.6424	0.6869	0.5658	0.5419	0.7149	0.5486	0.9342	1.0000	0.6602
NCT	0.7238	0.6068	0.5995	0.6764	0.6690	0.7582	0.7180	0.6371	0.6899	0.5641	0.5450	0.7178	0.5429	0.9302	1.0000	0.6534
LU	0.7368	0.6137	0.5953	0.6886	0.6308	0.7126	0.6821	0.6008	0.6932	0.5748	0.5471	0.7214	0.5528	0.9422	1.0000	0.6652
MR	0.7245	0.6111	0.5993	0.6771	0.5927	0.6708	0.6415	0.5644	0.6858	0.5669	0.5413	0.7137	0.5435	0.9354	1.0000	0.6541
FR	0.7407	0.6179	0.5941	0.6922	0.5611	0.6453	0.6070	0.5344	0.6321	0.5223	0.4924	0.6591	0.5557	0.9483	1.0000	0.6687
W	0.7613	0.6235	0.5880	0.7115	0.6788	0.7685	0.6976	0.6465	0.7060	0.5851	0.5384	0.7350	0.5711	0.9609	1.0000	0.6873
LCC indicator	0.5293	0.6087	0.5887	0.5749	0.7053	0.8361	0.7817	0.7953	0.9055	1.0000	0.9439	0.9399	0.5442	0.7152	0.7543	0.6215

The next step consists in defining a proper weight vector. The assignment of the relative weights to the criteria establishes an order of relative importance among the latter. In fact, the weights measure, through numerical dimensionless values, represents the properties that are assigned to the various aspects of the problem and for this reason they never have absolute value but only relative.

As shown in Section 7.9, the weight vector in the initial weighting configuration (Configuration 0) has been set up considering an equal weight distribution among the 3 groups of decision criteria, namely PC, EHP and LCC.

The best alternative that makes most of the three groups of evaluation criteria in the weight configuration 0 is the reconstruction strategy with HMAC as the binder layer and CMRA as the base layer (see Table 27). Instead, the alternatives with the traditional HMA as the base layer often qualify as the least performing and sustainable alternatives.

Table 27 – Ranking of the alternatives and score according to the results of MADM in weight configuration 0

Alternative maintenance strategy	Ranking	MADM score
HMA-HMAC-CMRA	1	0.69
HMA-HMMA	2	0.68
HMA-PMA	3	0.66
HMA-PMA-CMRA	4	0.66
HMA-PMA-HMAJ	5	0.64
HMA-HMMA-CMRA	6	0.59
HMA-HMA-HMAJ	7	0.58
HMA-HMAC-HMAJ	8	0.57
HMA-HMA-HMA	9	0.54
HMA-HMMA-HMAJ	10	0.52
HMA-HMAC	11	0.50
HMA-HMA	12	0.48
HMA-HMA-CMRA	13	0.47
HMA-PMA-HMA	14	0.45
HMA-HMAC-HMA	15	0.45
HMA-HMMA-HMA	16	0.43

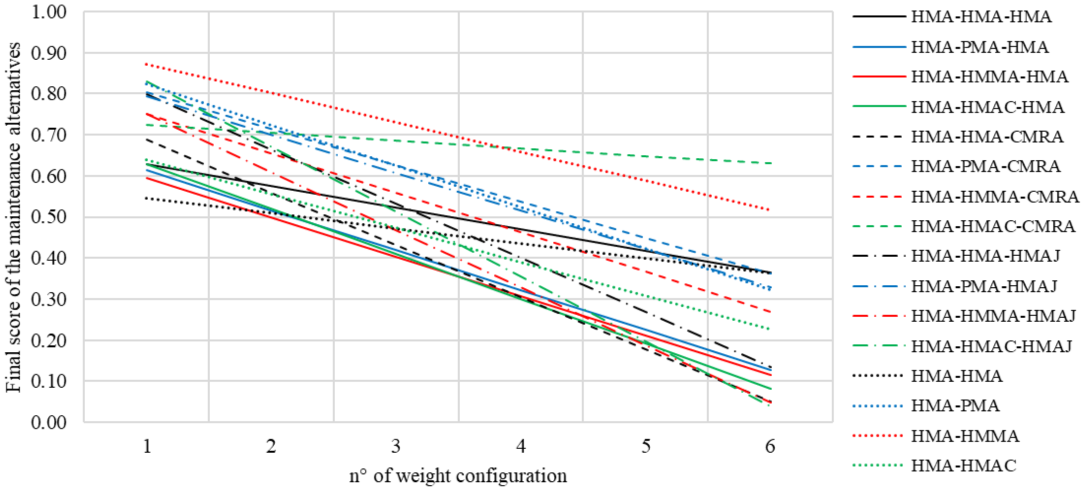
8.4.1 Sensitivity analysis

Sensitivity analysis plays an important role in verifying the robustness of a study's conclusions, confirming the credibility of the results if they remain the same under different assumptions. Therefore, the purpose of the present study is providing a sensitivity analysis of the stability of the obtained outcome considering the weight distribution among the evaluation criteria.
In this way it has been possible to take into account different evaluation procedures and different perspectives, as well as analysing the effect of the available data set on the optimal solution identified.

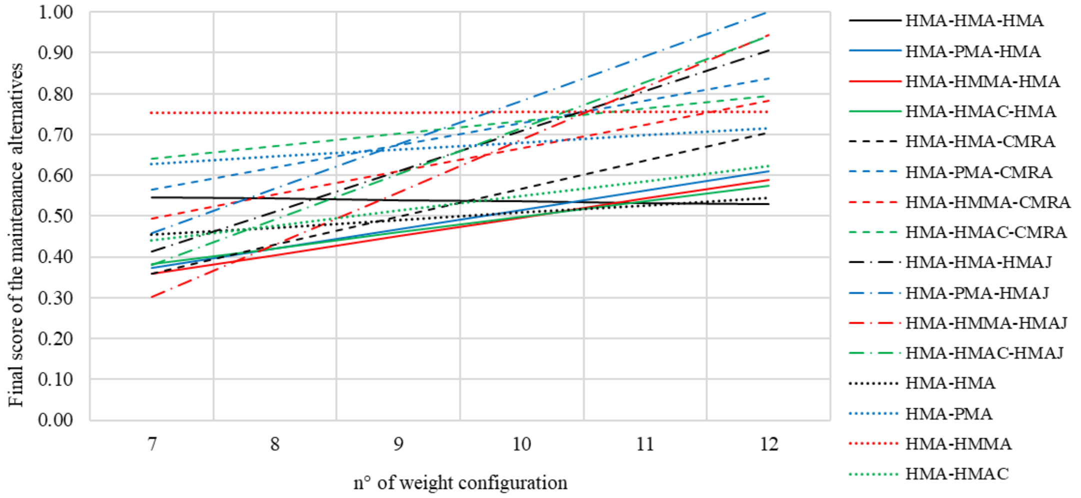
In order to carry out a sensitivity analysis also with respect to the available decision matrix, the proposed methodology has been applied to 18 different weight configurations (see Figure 10), in addition to the basic configuration, which are characterized by the lack of one and/or two dimension.

The overall frequency of appearance of the best alternatives was calculated through Equation 35. In detail, it is possible to notice that in 47% of the cases (weight configurations) the ideal solution occurs for the reconstruction strategy applying the solution with HMAC as the binder layer and CMRA as the base layer. In particular for the weight configurations that stress the importance of pavement performance and life cycle costs. Additionally, the reconstruction solution with PMA as the binder layer and HMAJ as the base layer outranked the other alternative maintenance solutions in 37% of the cases, mostly due to the best environmental performance and longest service life among the analysed solutions. Lastly, another result worth mentioning is the frequency of appearance as the best solution of the rehabilitation strategy with HMMA as the binder layer (16%), which well resists to rutting thanks to the superior performance in terms of stiffness in the high temperature range.

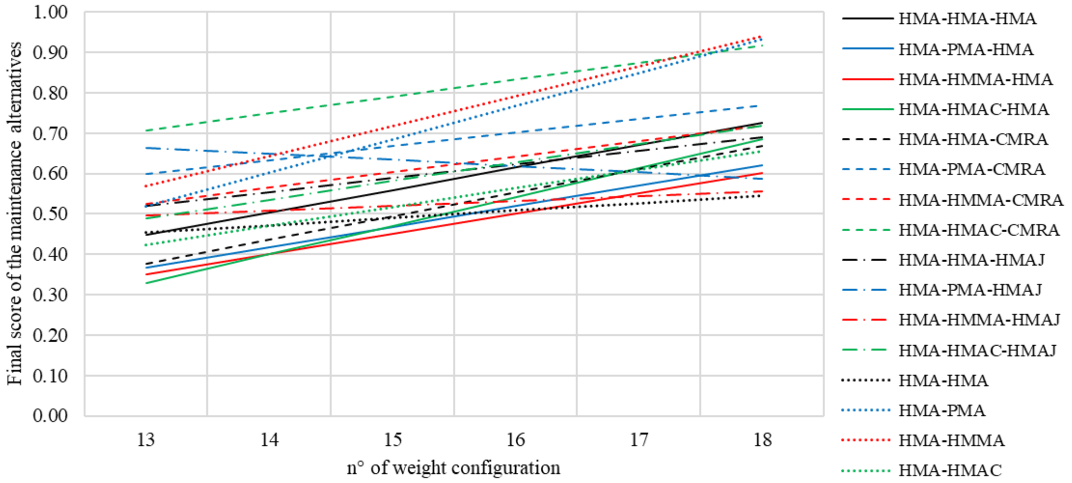
Among the outputs of the BIM analysis tool there is the scoring of each alternative maintenance strategy and its variation with the weight assigned to each group of decision criteria. The results reported in Figure 21a, b and c show respectively the score of each alternative when varying the weight assigned to CP, LCC and EHP, which the overall success of each alternative depends on.



a)



b)



c)

Figure 21 - Sensitivity analysis results. Variation of the score of alternatives when varying the weight assigned to: a) PC group, b) LCC group and c) EHP group

8.5 BIM analysis tools results and validation

The results reported in the present Chapter are the outputs of the application of the designed BIM analysis tools to an illustrative case study, which was functional to show and apply the PMS-LCA-LCCA framework, as well as check and validate the software results.

After equipping all the data templates with the necessary data to run the analyses, a series of checks were carried out to verify the correct functioning of the script:

- The PMS results of the BIM analysis tool (in terms of PCI calculation, number, type and timing of the maintenance interventions according to each maintenance strategy) were compared with the results obtained from the application of the same conditions run on Excel software [135], considering the same asphalt pavement stratigraphies and the same decay curves of R and FD; the results showed, apart from approximation errors, the script was correctly returning the maintenance program for each of the alternatives. Similarly, LCCA calculations were simulated on Excel and returned the same results as those obtained from the BIM-analysis tool;
- The LCA results obtained from the BIM analysis tool were compared with those of Simapro software [136]; again, the results obtained from the BIM tool were the same as those obtained with a tailored LCA software;
- The MADM results, in terms of ranking of the alternatives and frequency of appearance of the best alternative, were compared with those obtained with Mattrix software, a MADM software developed at University of Coimbra [137]. In addition to the simulation of the utility method and sensitivity analysis on the weight distribution among the criteria, Mattrix was leveraged to check the consistency of the MADM method itself; a series of analyses were run using different MADM methods: a) ELimination Et Choix Traduisant la REalité (ELECTRE) [138], b) EDIS [139], and c) Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) [140]. The results, briefly shown in Figure 22, highlight that the best compromise alternative suggested by the BIM analysis tool is the one that most frequently appears when applying alternative MADM methods, confirming the consistency of the results for the illustrative case study under analysis;

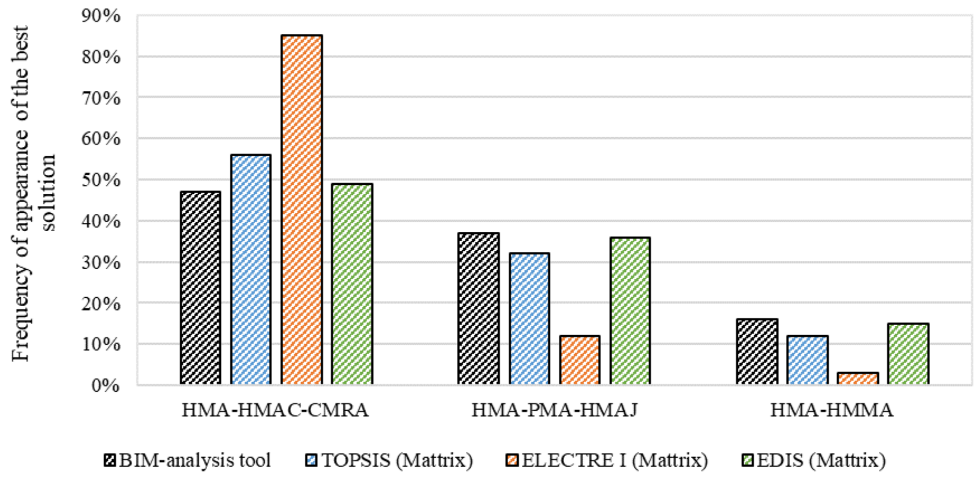


Figure 22 – Frequency of appearance of the best solutions of the BIM analysis tool versus the results of ELECTRE I, TOPSIS and EDIS application run on Mattrix software

- One of the expected results is the informatization of the pavement information model, which consists of assigning the outputs of the analyses to some automatically-created property sets, that are either associated to a specific layer or referred to the whole road corridor, like LCA and LCC indicators and the results of the PMS. After running the scripts, the mentioned property sets were filled with the results: Figure 23 and Figure 24 show the final information assigned to each property set, respectively the LCA indicators and LCC indicator together with the PMS and MADM results.

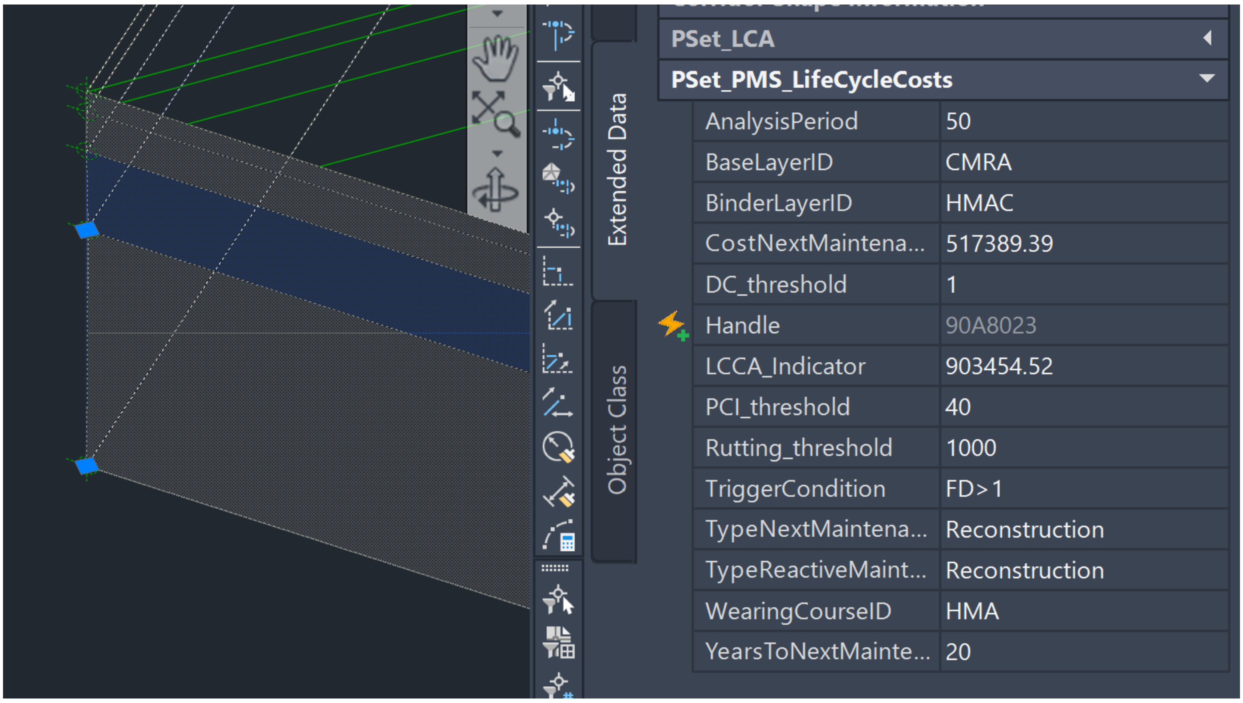


Figure 23 – Updated LCA property set as seen in the Civil 3D environment

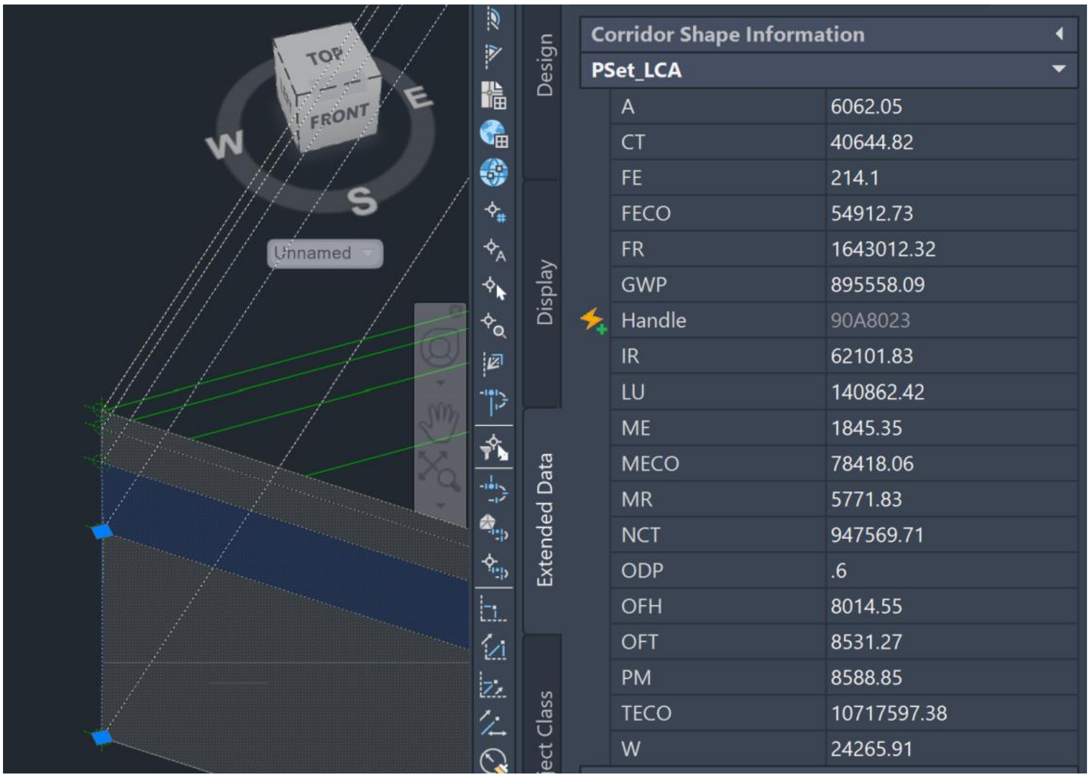


Figure 24 – Updated PMS and LCC property sets as seen in the Civil 3D environment

- The last validation step referred to the computational time of the whole BIM analysis tool, with particular reference to the variation of the computational time when changing the analysed set of alternative. Moving from just 1 to 100 alternative maintenance alternatives, the computational time shifted from 1 s to 8 s when running the script on a medium-high performance hardware. Although the computational time variation could pose problems in applying the analysis tool in the case of a very high number of alternatives, for example when dealing with the modelling of a network or a portion of it, it is compliant with the analysis of a rather long single pavement section that is the illustrative case study of the analysis.

9 Conclusions

The complexity of the current socio-economic system even today benefits from a linear economy model since companies, not very responsive to market stimuli, act independently of each other, making it difficult for them to enter a virtuous and economic sustainable loop of recovery and recycling waste.

With the concepts of sustainability and life cycle thinking becoming more important in the field of asphalt pavements, designers are expressing a growing need for delivering sustainable pavements, analyzed through LCA. At the same time, BIM tools can facilitate and automate the management of complex information in infrastructure projects and converge towards sustainable decision-making strategies. However, a sustainability assessment is a complex process and an integrated approach for implementing sustainable aspects in the asphalt pavement design decision-making process is currently lacking. The present work provides an effective framework to approach the use of BIM platforms to provide additional analysis tool oriented towards sustainability in the field of road asphalt pavements, helping assess the potential environmental impact and costs borne by the managing bodies for the construction/maintenance treatments, expressed through multiple environmental and cost indicators calculated according to LCA and LCCA methodologies. The proposed LCA tool expands the current knowledge on BIM-PMS-LCA-LCCA integration oriented towards the promotion of sustainable pavement recycling practices.

The present study aimed at the elaboration of a BIM-based methodology related to the management of pavement data and the drafting of pavement maintenance plans involving a library of designed asphalt pavement solutions. The main objective was to create a methodological structure implemented in a BIM environment for the automated analysis of the deterioration state of a road pavement through specific condition indicators, namely the Pavement Condition Index, the cumulated fatigue cracking damage, and the rut depth. The implemented methodology also allowed to obtain detailed information regarding the pavement condition and the optimum maintenance intervention given a selected library of design solutions.

The synergistic effects of several innovative and traditional asphalt mixtures for binder and base layers of asphalt pavements were analyzed from both the performance, cost and environmental points of view by designing alternative asphalt pavement stratigraphies and assessing the environmental impacts of the life cycle of these pavement configurations, applied within a case study of a 1-km road section located in southern Italy.

Once run the BIM-based analysis tool, the digital objects of the pavement BIM were enriched with additional property sets collecting the results of MADM, in particular referring to the alternative maintenance solution that appeared more frequently as the best solution when varying the weight distribution among the decision criteria.

The in-depth analysis of the life cycle, the construction of a detailed life cycle inventory, the environmental and cost assessment returned by the BIM analysis tool allowed drawing the following conclusions:

- CDW recycling into an HMAC binder layer gives considerable benefits in terms of water consumption reduction during natural aggregates production, lower emissions of PAH and chlorofluorocarbons to air, as well as lower emissions of phosphorous compounds released into water in comparison to a traditional HMA binder layer;
- The wet (HMMA) and dry (PMA) modification of asphalt mixtures entails additional environmental burdens compared to the traditional HMA binder; nevertheless, the PMA lowers the human carcinogenic toxicity through the reduction of polycyclic aromatic hydrocarbons and particulate matter released during the recycling and manufacturing phases of plastic pellets compared to traditional industrial modification of bitumen with virgin polymers;
- The main source of variability of the environmental impact category indicators was the adoption of the cold in-place recycling technology for the reconstruction of the base layer, which lowered all the impact category indicators on average: −22% for CMRA versus the HMA base layer. In particular, the substitution of natural aggregates with RAP lowers the emissions in water in terms of nitrogen and phosphorous compounds emitted during natural aggregates’ production and supply to the asphalt plant;
- The asphalt materials that showed the best synergy between the minimization of environmental impacts and maximization of the service life of the pavement solutions were the PMA combined with the base layer HMAJ, increasing the service life of a traditional HMA stratigraphy by 11 years.

The designed computational tool, scripted using a combination of visual programming language and Python programming language, looks a promising application to enrich the informative content of the model and leverage BIM as an analysis tool; the analysis of the computing time showed little variation with the growing number of maintenance alternatives, confirming the applicability of the procedure for more complex projects.

From the point of view of the potential impacts of the present work in the road industry, decision-makers and road managing bodies could benefit from the use of the developed methodology and application; the results of the work represent a necessary innovation to comply with the future needs of both the local Legislative frameworks regarding the mandatory application of Building Information Modelling to public bidding processes and the adoption of Minimum Environmental Criteria to spread sustainability across the conception, design and operational stages of the life cycle of an infrastructure.

The main limitations of the work, which is not intended to provide an exhaustive approach to the problem of PMS-life cycle management integration, may be summarized in the following points that require further investigation:

- The lack of an uncertainty analysis to investigate the uncertainty of variables that are used in decision-making problems in which observations and models represent the knowledge base. In complex decision-making problems, uncertainty analysis would help making a technical contribution to decision-making through the quantification of uncertainties in the relevant variables;
- The inclusion of the social aspects through Social-LCA to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle. Social-LCA looks at the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling and final disposal, making use of generic and site-specific data and complementing the LCA and LCCA;
- The extension of the problem of road maintenance management using life cycle indicators to the network level. BIM road infrastructure management solutions should ultimately help the user collect, maintain and analyse road assets, delivering a central platform upon which users can plan, operate and maintain an ever-improving intelligent transportation network. Included are the geospatial location of these assets, the graphic representation of these networks and their geospatial context in map form.

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