A systematic digitalization for climate mitigation and adaptation measures in long-term road planning

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Abstract. Facing the growing challenges posed by climate change, the importance of integrating climate mitigation and adaptation measures in long-term road planning has become increasingly unavoidable. From the road designs with materials and constructions, maintenance planning and towards the material circularity, an integral assessment is critical for infrastructure management, with decisions made today having far-reaching implications for the future. This paper underscores the pressing need for systematic digitalization in road planning, augmented by the life cycle assessment (LCA), and the key benefits of leveraging materials knowledge in this process due to their significant weight in the impact. Systematic digitalization offered by ORIS Materials intelligence involves the data collection, analysis and usage of various datasets regarding materials, climate, traffic towards environmental and social parameters, to enable more informed decision-making. Advanced modeling, automatic simulation techniques and effective visualizations allow planners to evaluate the climate exposures, as well as network vulnerability, and craft climate adaptation strategies for enhanced resilience. Moreover, the emergence of such digital capabilities offers a unique opportunity to systematically and consistently assess alternative designs and deliver low impact infrastructure, by connecting local materials data with engineering expertise to simulate the cost and carbon performance through a road life cycle. The LCA model also predicts the impact from Pavement-Vehicle interactions and the effect of albedo and carbonation, which enables an inclusive decision-making process through a whole value chain. Recent studies have resulted in up to a 30% reduction in cost, 50% in carbon and 80% in resource utilization.

Keywords: Digitalization, Pavement, Life cycle assessment, Mitigation, Adaptation, Material intelligence

1 Introduction

1.1 Strategic material selection

The selection of materials and the design of pavement critically influence both the economic and environmental aspects of road construction projects. Notably, these factors account for approximately 60% of the total project cost and an estimated 85% of the cumulative greenhouse gas emissions [1]. Traditionally, road designs are predicated on standardized and historical methodologies, with considerations for material availability and suitability being relegated to the latter stages of construction. This is primarily attributed to the challenges inherent in data collection and the absence of a systematic approach. Consequently, this prevailing practice among various stakeholders in the road ecosystem—including owners, investors, designers, and contractors—fails to adequately incorporate essential sustainability considerations, such as climate change mitigation, natural resource conservation, and socio-economic equity. Decision-making in an early design stage in the construction project is crucial to save cost and reduce greenhouse gas emissions by selecting right materials and right designs of infrastructures.

1.2 Data-driven infrastructure project management

In the realm of data integration, the infrastructure sector confronts the complexities of managing vast and heterogeneous data sets. This challenge necessitates a sophisticated data integration process, capable of handling diverse data characteristics. Such integration is crucial for optimizing project outcomes and enhancing overall efficiency of projects. However, the sector still faces obstacles in adopting these technologies at scale due to risk associated with new and untested technologies, alongside a general lack of awareness and comprehensive training.

The digital transformation of infrastructure projects has become a focal point reflecting its significance in the modernization of construction practices. A growing number of literatures underscores the role of Building Information Modelling (BIM) in revolutionizing the long-term infrastructure management from the planning, design, maintenance program, up to demolition/renovation. For instance, Lafioune et al. [2] discusses the digital transformation to enable comprehensive and asset management through a whole infrastructure life cycle within the municipal context. The framework developed in this study helps municipalities provide better services, optimizing planning and work execution of construction projects such as roads, railways, bridges while fostering resilience and sustainability. Its originality lies in aligning asset management with digital transformation. Liu et al. [3] suggests a conceptual framework that incorporates BIM with a sustainability metrics plug-in, facilitating “what-if” scenarios to improve sustainability decision-making. Meanwhile, Consilvio et al. [4] and Oreto et al. [5] evaluate the impact of BIM-based infrastructure projects, highlighting the predictive analytics to revolutionize maintenance program management. The digital platform facilitates the early detection of potential issues, scheduling timely maintenance activities and optimizing resource deployment. This approach to maintenance not only extends the lifespan of infrastructure assets, but also reduces the operational cost and proposes long-term climate mitigation and adaptation measures. The utilization of artificial intelligence and machine learning in predictive maintenance and the optimization of resources is pivotal for enhancing project automation, detailed in research by Yao et al. [6]. These tools create virtual replicas of a physical asset at a very early stage of the project, allowing for dynamic simulations, infrastructure performance tracking, scenario analysis, thereby enhancing long-term management and strategic planning of infrastructure projects. These technologies allow for analyzing large datasets to predict optimal selection of resources, its transportation, and a whole life cycle carbon and cost performance. Moreover, these tools enable the measurement and analysis of carbon emissions throughout the whole life stages of a project, from the extraction of raw materials, their transport and transformation into final products, operation, demolition and even the loads and benefits for future life cycle from demolished waste materials. Lastly, the critical aspect of these digital transformations of infrastructure projects is the visualization of LCA modeling and results, which play a pivotal role in decision-making. Hollberg et al. [7] emphasizes the growing importance of visualizing LCA results in the construction design process. Visual representations of data enable stakeholders to grasp complex environmental impacts more intuitively, facilitating more informed and sustainable choices.

In these evolving management of infrastructure projects, a data-driven approach has made significant strides for enhanced decision-making and efficiency through a whole project cycle. Despites these advancements, there remains a notable gap related to the absence of 1) automatic connection of real time and local material availability to construction projects, 2) a comprehensive single platform for holistic analysis in long-term road planning and 3) consistent and systematic approach enabling full and easy pavement LCA. Also, the data collection phase is very time-consuming and costly. Addressing these shortfalls, the current study introduces a material platform, complete with extensive databases of materials, tailored to connect directly with an infrastructure project. This platform stands out by automating the process of life cycle carbon footprint and cost analysis, thus integrating sustainability directly into the project lifecycle.

2 Digital framework for pavement LCA

2.1 General introduction to the developed framework

Negishi et al. [1] demonstrated a digital framework tailored for road infrastructure projects integrating a comprehensive system boundary that encompasses the entire project life cycle from the early conception phase to the management of demolished waste operations or renovations. Fig. 1 shows the architecture of the digital framework for pavement LCA. Central to this framework is an elaborated material database, meticulously designed to integrate and manage data pertinent to a whole value chain of the project. This database encapsulates every aspect of the project environment, including local material sourcing, transportations, construction and long-term maintenance operations, and end-of-life management. Its versatility allows it to adapt to various study objectives, whether it is used for measurement, reduction management, local material procurement, scenario analysis, or external communications as examples. Moreover, its adaptability to different system boundaries and scope of diverse infrastructure projects makes it an invaluable asset, capable of being tailored to the unique requirements of each project.

The carbon footprint assessment in the tool adheres to product level LCA standards (ISO 14067, EN 15804, and ISO 21930) extended to the project level assessment by encompassing the entire life cycle of the road. The use phase models compute two aspects of the effect of material properties: one focuses on road surface properties, evaluating the albedo effect, carbonation and road surface lighting, while the other examines Pavement-Vehicle Interaction (PVI) assessing fuel consumption changes due to pavement wear and rolling resistance effect. The methodology incorporates both pavement degradation and enhancements from maintenance activities into these calculations. Furthermore, it also estimates the carbon emission benefits from material recovery scenarios. This comprehensive approach aids in pinpointing opportunities for reducing the carbon footprint and informs decision-making processes, thus preventing unintended consequences.

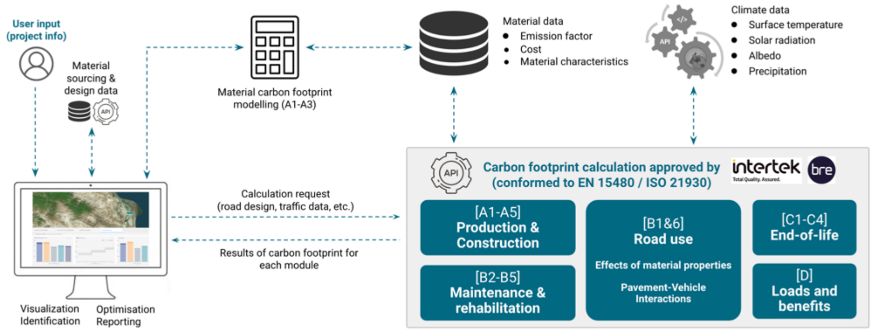


Fig. 1. Digital framework for pavement LCA based on Negishi et al. (2022).

2.2 Material data integration

The material data collection methods combine data sourced directly from specific projects with publicly available information. This ensures a rich and accurate database, essential for the detailed analysis of various material properties and their carbon footprint. Each material entry in the database includes a Declaration of Performance (DoP), which provides critical information about its characteristics, carbon footprint and prices.

Carbon footprint associated with materials is from the sources aligned with LCA standards and specific to the geographical context. By default, a generic database such as ecoinvent is primarily used but the platform is capable of easily integrating local and/or national databases. Cost data of materials are incorporated based on a local survey and local experiences. These data also are collected from the local project team and finally embedded into the database of the platform. The platform geographically visualizes material production sites, each of which has one or multiple types of products. A product is then characterized with attributes such as carbon footprint, cost, mechanical properties, and other information from the DoP.

The material database encompasses a wide range of production sites of principal infrastructure materials such as asphalt, concrete, cement and steel. This extensive coverage is further augmented by its expansion not only across various European countries including France, Germany, Finland and the United Kingdom, but also including other regions such as the Middle East, Central Asia, North America and Latin America. This geographical diversity is not limited and ensures to reflect regional or local material availability, standards thereby enhancing its applicability. Utilizing machine learning (ML) and deep learning (DL) techniques, data is meticulously mined and refined from a variety of publicly available sources. A notable example of this sophisticated data acquisition process is the utilization of satellite image recognition. The integration of such cutting-edge technologies not only bolsters the accuracy and comprehensiveness of the database but also significantly enhances its utility in supporting informed decision-making for sustainable road projects.

3 Digitized project workflow

The overall workflow is outlined in Fig. 2 and includes five main steps including the project alignment, set up to the project environment, analysis of the bill of quantities (BoQ), analysis of Key Performance Indicators (KPI) and result visualization and decision making. The whole process is iterative, and the platform allows at any phase of the project coming back to the upstream phase and refining the modeling. These processes are linked with internal and external databases or models via Application Programming Interface (API). The following sections explain step by step the project workflow realized in the platform.

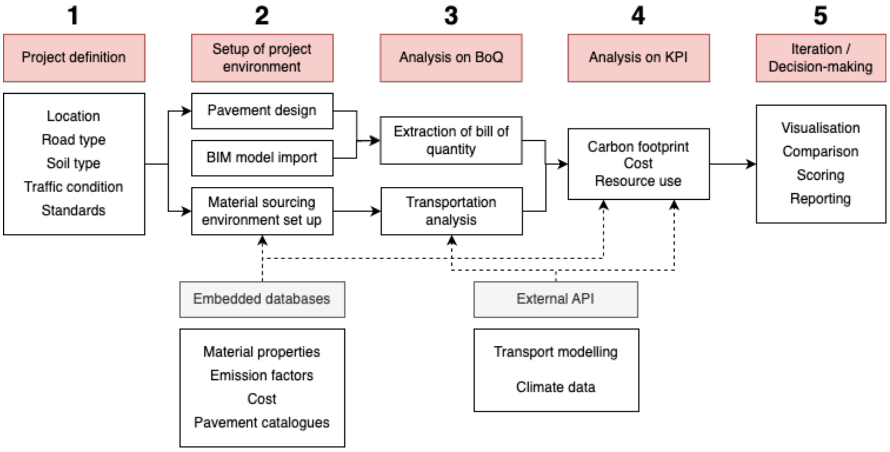


Fig. 2. General workflow of digitized life cycle assessment of pavement toward a decision-making.

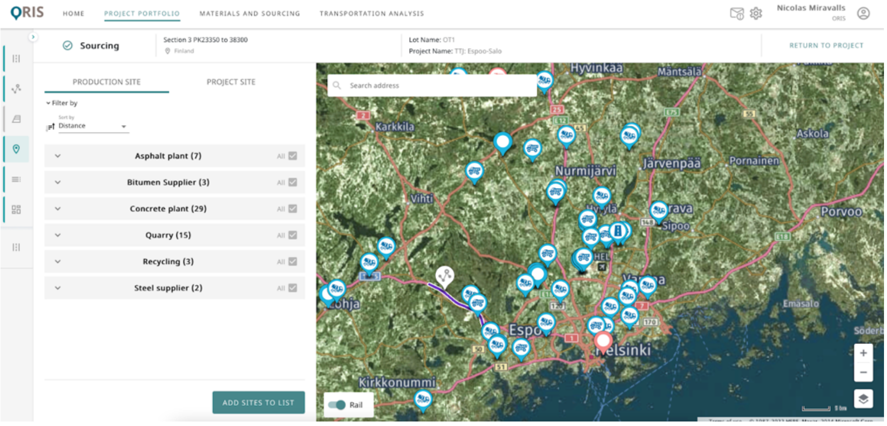
3.1 Project definition

The platform's configuration to a specific project environment begins with a detailed project definition. This definition includes various aspects such as the type of infrastructure, its location, the dimensions of the project, and adherence to local standards and regulations of infrastructures and materials. Subsequently, the project must designate one or several access points, which serves as critical hubs for the supply and subsequent transportation of materials, forming the basis for material transport analysis. From the LCA perspective, this phase corresponds to the goal and scope definition. The functional unit can be defined as for example "construction of the 10 km rural roads with 4 m width connecting the city A to B for the reference service life of 30 years, with expected annual traffic growth of 2% per year" or "reconstruction of the existing asphalt pavement of 50 km highway with 4 lanes to extend the service life of 25 years."

3.2 Setup of the project environment

An integral part of this process involves defining a search area for potential material suppliers, typically demarcated as a radius distance from each access point. Fig. 3 demonstrates an example of the material suppliers map, identified around the location of the project. The viable material sources are logistically, economically and environmentally identified from the embedded material database. However, the practical scenario involves a contractor who is awarded the project and is responsible for making decisions. This is the reason why the platform allows a personalized selection of the preferred supply option in order to simulate, assess and compare every scenario. The location of a project is a significant factor, influencing both the selection of materials and the overall logistics of their transportation to the site. Local transportation constraints such as speed limit, weight limit or interdiction of carrying dangerous materials, are taken into consideration to find optimal transport itinerary. This tailored approach ensures that each project's specific needs and environmental factors are adequately addressed, optimizing efficiency and feasibility.

The information of these sites is verified and completed by using data science techniques. Once material sourcing sites are identified, the attributes of materials required for the successful completion of the database is collected from various data sources including data provided by clients and data available in public. Each material is accompanied by the Declaration of Product (DoP) that provides material characteristics. Material prices are provided from contractors introduced in a cost table dedicated to a project, while environmental datasets associated are from the sources aligned with LCA standards and specific to the geographical context. To address the difficulty of obtaining environmental data and the harmonization issues with respect to LCA standards, the platform has the capability to integrate different sources of environmental data aligned with EN 15804+A2 or ISO 21930. By default, ecoinvent is utilized, providing the viable datasets to each location on a country level or more global level. This is completed by average data from industries or national databases (e.g., average EPDs from a European admixture association) or national databases (e.g., Base Carbone® for France, CO2data database for Finland) if no corresponding data is available in ecoinvent. Furthermore, each project has the flexibility to customize its material environmental datasets by users allowing them to be used as project's representative values. Alternatively, if local regulations specify databases to be used, these can replace the default database provided by the platform.



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Finland
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Project Name: TTJ: Espoo-Salo
Sort by Distance

Fig. 3. Materials sourcing site map around Helsinki in Finland.

3.3 Analysis of the bill of quantities

This phase involves extracting a detailed bill of quantity or so-called Life cycle inventory (LCI) data starting with the definition of pavement structures. The design of pavement structures can be approached either through manual input or automatic selection from digitized local catalogs. In the manual method, detailed specifications for each pavement layer must be inputted into the platform. This includes information about the layers' dimensions, materials used, material density, internal transport costs, and overall pavement cost. Conversely, utilizing digitized local catalogs requires inputting general road information aligned with local regulations and standards. Such information comes from the first alignment information given in the previous step and encompasses the country, road type, traffic volume, soil classification, local climatic conditions, and material transportation modes. Upon entering these parameters, the platform leverages its database to automatically propose pavement solutions tailored to these specific inputs. It is crucial to acknowledge that the methodologies for structural design, criteria for layer sizing, and the range of materials available vary significantly from one country to another. Consequently, pavement designs are not universally standardized and vary based on regional specifications. From the selected solutions, the platform extracts fundamental data such as the dimension (width, thickness, angles) and material density. BIM models with the Industry Foundation Classes (IFC) format, which is a standardized and digital description of the infrastructure based on ISO 16739-1:2018 [8], can also be used and connected to the platform from which the analysis on bill of quantities is automatically effectuated.

The ORIS platform provides a comprehensive carbon footprint assessment through all the stages of pavement lifetime, thus including the quantification of LCI related to maintenance operations. The specification of maintenance equipment is characterized in detail within the embedded database, facilitating the automatic calculation of energy consumption based on the maintenance programs. However, the platform does not suggest maintenance programs, recognizing the complexity of estimating the service life of pavement and the highly variable aging models across materials, companies and scientific methodologies. Rather, the user can configure the maintenance program based on different models or proven references such as national guidelines, personal experiences, and expectations on design service life.

Moreover, construction and maintenance scenarios that require unique site installations or the mobilization of heavy equipment necessitate a project-specific calculation, whereas scenarios of equipment demands are distinct. It is essential to monitor the capacity of local resources and the environment to precisely assess the impact of transportation and the distances required to maintain assets using various solutions. The breadth of road maintenance techniques—including but not limited to removal, topping, and replacement, milling, recycling, and full depth reclamation—requires complex comparisons and simulations to ensure optimal decision-making across multiple criteria (cost, carbon footprint, circularity, resilience). The digital platform as ORIS thus facilitates the evaluation and comparison of the impacts of each model by systematically aligning the magnitude and frequency of maintenance works.

3.4 Analysis of Key Performance Indicators

The B1 and B6 modules' calculations are automated in a total of six distinct models based on the following references: roughness [9], deflection [10], texture [11], albedo [12], lighting [13] and carbonation [14]. Firstly, the increased energy consumption due to pavement-vehicle interactions is determined by considering the vehicle rolling resistances. Concurrently, the albedo effect and lighting consumption are estimated, considering the surface material of the pavement and prevailing climatic conditions. For pavements with a concrete surface, the extent of carbonation over the road's entire lifespan is quantified. Vehicle traffic con-tributes to the deterioration of the pavement's surface and structure, which in turn impacts vehicle fuel consumption due to altered surface conditions. Maintenance programs play a crucial role in these calculations; they restore or improve the pavement condition compared to its state prior to maintenance. This restoration or improvement is factored into the overall assessment, providing a comprehensive understanding of the pavement's impact on vehicle energy use and the environmental footprint of the road infrastructure.

Upon the establishment of a material sourcing sites database and the identification of the project location, all the possible transport itineraries are automatically simulated, with which its corresponding time, carbon footprint and cost are associated. The most suitable route is then determined. This selection process considers various road constraints, such as permissible truck size, weight limits, as well as environmental avoidance zones.

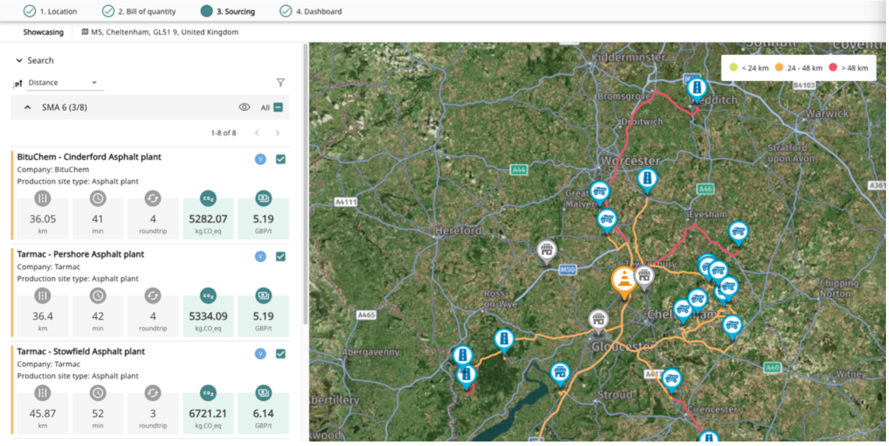
3.5 Result visualization and decision-making

The final phase of an LCA consists of result interpretation, which includes visualization, scenario comparison, reporting of outcomes. The platform facilitates decision-making by offering various design comparison options and rating systems. By providing a comprehensive assessment framework to evaluate various aspects of the project in a single platform, the project management to reduce the impacts is possible from a different perspective of involved stakeholders in the project and in each life cycle stage. The solution for reduction should be the combination of material supplier selection, transport logistic optimization, material choices, and the utilization of recycled materials. Each of these elements is meticulously scored based on their sustainability impacts. Additionally, the tool offers detailed results that aid in identifying hotspots and areas of improvement. This level of granularity is instrumental in identifying specific phases or aspects of the project where the greatest carbon and cost inefficiencies occur. Such insights enable targeted interventions for optimization.

Crucially, the tool's capabilities extend to optimizing the entire value chain of the road project. It enables strategic selection of suppliers by considering factors like proximity, time and cost effectiveness and low carbon transport (Fig. 4). Transportation optimization is achieved by analyzing routes, vehicle types, and logistic strategies to minimize carbon emissions and costs. In terms of material choice, the tool evaluates not only the cost and performance but also the carbon footprint, promoting the use of sustainable and recycled materials.

Fig. 5 visualizes an analysis of material sourcing for a real construction project in the U.K. It includes estimations of material costs, carbon footprint and transport distance for materials used in each layer of a pavement design. The minimum and maximum cost and carbon footprint associated with material use helps to understand the potential of these optimizations within identified material suppliers. At the bottom right, there's a summary section that presents the total minimum cost estimation, total minimum carbon footprint, and total material consumption for the project.

Moreover, the tool facilitates the exploration of alternative construction methods, adoption of low carbon energy sources, aligning with the industry's shift towards greener practices. By integrating these diverse aspects into a single platform, it provides a holistic view of the project's life cycle, thereby empowering stakeholders to make decisions that balance cost and carbon footprint. This systematic approach aims to enhance the sustainability profile of road infrastructure projects from design to completion. In parallel, the evaluation includes climate risk screening with vulnerability assessments to enhance climate resilience in road infrastructure. By scaling climate exposures (heat, precipitation, freeze-thaw cycles, flooding) from insignificant to severe, and correlating these with road quality and traffic conditions, it provides a nuanced climate risk score. This scoring system is pivotal for identifying specific vulnerabilities of roads in varying geographic contexts. This approach allows for targeted climate adaptation measures, ensuring roads are better prepared for diverse climate impacts.



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BituChem - Cinderford Asphalt plant ☑
Company: BituChem
Production site type: Asphalt plant
36.05 km | 41 min | 4 roundtrip | 5282.07 kg.CO₂eq | 5.19 GBP/t

Tarmac - Pershore Asphalt plant ☑
Company: Tarmac
Production site type: Asphalt plant
36.4 km | 42 min | 4 roundtrip | 5334.09 kg.CO₂eq | 5.19 GBP/t

Tarmac - Stowfield Asphalt plant ☑
Company: Tarmac
Production site type: Asphalt plant
45.87 km | 52 min | 3 roundtrip | 6721.21 kg.CO₂eq | 6.14 GBP/t

Fig. 4. Material sourcing simulation evaluated with travel distance, time and associated carbon footprint and cost (orange point: access point to the construction site, bleu/grey point: material sourcing site, and colored line: simulated transport itinerary).

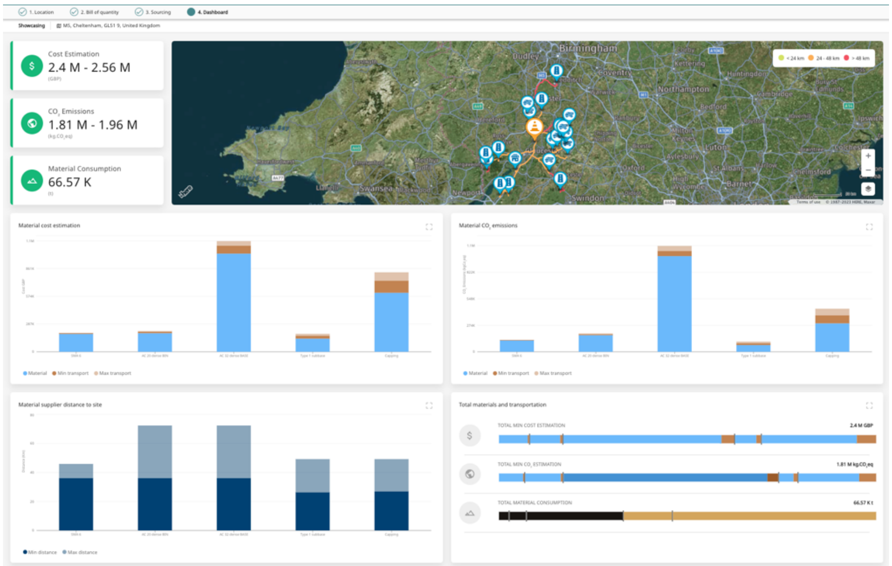

Fig. 5. Example of result overview (focus on A1-A4) of a typical road construction project.

4 Conclusions

The advent of digitalization and advanced data science techniques heralds a new era for sustainable road infrastructure decision-making. The crux of successful projects implementation, particularly in achieving significant reductions in carbon footprint by up to 50%, cost up to 15% and resource consumption up to 80%, lies in the early-stage assessment of the project. The digitized framework discussed in this paper is pivotal in enabling rapid and efficient analysis of a road project's performance across its entire service life.

This platform creates a dynamic link between real material markets and construction projects, integrating an extensive catalog of pavement solutions tailored to specific structural and local requirements. The possibility of BIM based modeling of pavement LCA from the add-on option of BIM software such as Civil 3D accelerates the assessment, thus making decision-making smoother. Such a technology simplifies the pavement design process at the preliminary stages of a project. Additionally, the framework enhances the safety and efficiency of pavement solutions by incorporating the International Road Assessment Program (iRAP) methodology into its analysis flow. This integration ensures that the pavement designs not only meet technical and environmental requirements but also adhere to safety benchmarks, thereby delivering comprehensive and sustainable infrastructure solutions.

The visualization and decision-making capabilities further underscore its utility in supporting informed choices that harmonize economic, environmental and material considerations. It represents a significant advancement towards operationalizing sustainability in road projects and, offering systematic and consistent approach.

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