Life Cycle Sustainability Assessment (LCSA) of pavements – A case study highlighting challenges and potentials

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ABSTRACT: Considering the significant impacts of roads on society, economy, and environment, measuring the sustainability performance of pavements is critical. Therefore, this contribution explores the application of Life Cycle Sustainability Assessment (LCSA) by the presentation of a case study of a motorway segment in Germany. The results show that the main hotspots for the environmental and economic dimensions are related to the use stage, specifically maintenance and replacement. Regarding the social dimension, social risks such as discrimination and unfair working conditions were identified. In general, LCSA enables a systematic assessment of the sustainability performance of roads allowing the identification of life cycle stages and processes that can later be improved to reduce impacts, while avoiding burden-shifting. However, the method presents several obstacles, some of them relating to the definition of consistent system boundaries and lack of reliable data.

1 INTRODUCTION

The impacts of roads in society and environment are widely known, and several efforts have been recorded towards measuring and improving their sustainability performance (Del Rosario & Traverso 2023). For instance, the Federal Highway Administration (FHWA) in the United States provides several tools in which the sustainability of pavements can be measured using methods such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and sustainability rating systems (FHWA 2021).

LCA is a method for quantifying environmental impacts of products throughout their whole life cycle standardized by the ISO 14040 and ISO 14044 (ISO 2020a, 2020b). LCA is widespread across many fields, and enables the identification of environmental hotspots associated to a particular product. LCC is a further life-cycle-based method addressing the economic dimension, i.e., the life cycle costs of products (Swarr *et al.* 2011). Although there are no general standards for LCC, a norm for its application in buildings exists (ISO 15686-5), which is often used as reference in road construction. Finally, the social performance can be addressed with Social Life Cycle Assessment (S-LCA), in which positive and negative impacts of products can be quantified (UNEP 2020). This method has been recently standardized by the ISO 14075 (ISO 2024).

All these methods are useful for measuring the performance of products in individual sustainability dimensions. However, sustainability should be addressed from a holistic perspective to avoid issues such as burden-shifting. This comprehensive approach can be achieved with the Life Cycle Sustainability Assessment (LCSA), which prescribes the parallel application of LCA, LCC, and S-LCA for the same functional unit (FU) (reference) and equivalent system boundaries (Kloepffer 2008; Finkbeiner *et al.* 2010). Although gaining popularity, this method is not yet widely adopted in the road construction sector, with only a few examples found in literature (Del Rosario & Traverso 2023).

Therefore, the aim of this contribution is to explore LCSA of pavements through the analysis of a case study. The objective is to provide insights on the potentials and challenges of this method in the road construction industry.

2 METHODS

2.1 *Case study*

The illustrative case study consists of a 5-km motorway segment near Dresden, assumed to have a Standard Cross-Section RQ 36 (FGSV 2008). The structure is assumed to have the load class BK100 and an Annual Average Daily Traffic (AADT) of 42,500 vehicles. The assessed structure is presented in Figure 1.

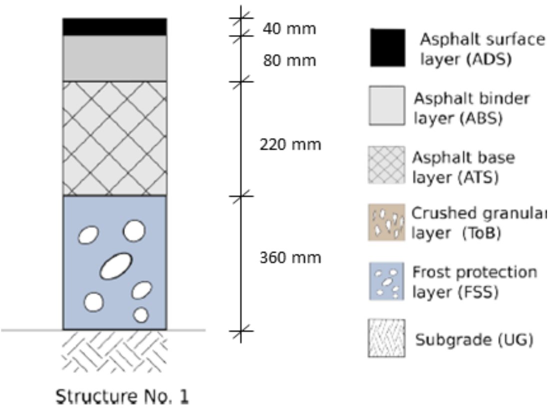

Figure 1. Pavement structure.

2.2 *Goal and scope definition*

The goal is to determine the main impacts of the construction and operation of a motorway section in Germany. In particular, the main hotspots and challenges shall be identified. The environmental and economic impacts are determined using the LCA and LCC methods. Due to lack of specific data that enables the determination of social impacts, social risks are determined to identify relevant social aspects.

The FU is 1 road-km of road pavement of a German motorway section near Dresden, with the standard cross-section RQ36, load class BK100, AADT 42,500 (truck share: 8.24%) and a period of analysis of 30 years.

Due to the granularity needed in each of the methods, the system boundaries of the study vary. In this simplified assessment, the LCA and social risk assessment consider raw material and energy production (A1), raw material transport (A2), asphalt mixing process (A3), asphalt mixture transport (A4), pavement construction (A5), maintenance (B2), and rehabilitation / replacement (B4). A period of analysis of 30 years is selected, in which following activities are assumed to be carried out:

- Years 1-30: Yearly winter service, inspections and condition monitoring
- Year 12: Thin asphalt overlay
- Year 16: Replacement of the surface layer
- Year 18: Thin asphalt overlay
- Year 30: Replacement of surface and binder layers

Since the LCC is conducted from a road agency perspective, production-related costs arising in Modules A1-A3 (e.g., raw material, labor, energy, supplies, overhead, etc.) are considered as part of the final cost (i.e., the costs mentioned above for production, plus marketing costs, profits, etc.). For the sake of harmonization with the reported LCA results, material costs within the initial construction will be reported as Module A3. Costs arising in Modules A4-A5, B2 and B4 are also reported.

The LCA was carried out using the software ©GaBi ts 10.6.2.9. For the LCC and the social risk assessment, the data was gathered from their respective sources (see Section 2.3) and processed using MS Excel. The norms ISO 14040, ISO 14044, ISO 15686-5, and EN 15804 were used as references for the assessment, as well as the UNEP LCSA Guidelines (UNEP 2011; ISO 2017, 2020a, 2020b; CEN 2021; ISO 2024).

2.3 *Life cycle inventory*

Secondary data was used for the assessment. Considering that the case study is located in Germany, German datasets were preferred whenever available. For the LCA, the databases ©GaBi Professional 2022.2 and Ecoinvent v.3.8 were used.

To conduct the LCC, data was obtained mostly from the Autobahn GmbH – road agency managing German motorways – and Baupreislexikon – a German costs database. The cost categories of material, transportation, labor, and machines are considered. Furthermore, costs related to tendering and planning commissioning, as well as construction site equipment were obtained as lump sums.

The social risk assessment was conducted with the Product Social Impact Life Cycle Assessment (PSILCA) database (GreenDelta 2020). Here, the social risks associated to stakeholders (e.g., workers, value chain actors, society, and local community) within a particular economic sector of the selected country are mapped and classified from “very low” to “very high” risks. For this study, the economic sectors associated to the life cycle of the pavement were identified based on Del Rosario et al. (2024) with the addition of activities for construction, maintenance and replacement, all considered to be under the sector “basic construction”.

2.4 *Life cycle impact assessment*

The Environmental Footprint (EF) method 3.0 was used in the LCA and all impact categories included were determined. These results were normalized and weighted using the factors of the method. In this study, only the most relevant impact categories are reported, which are those with a combined contribution amounting to at least 80% of the total environmental impacts after their normalization and weighting.

In the case of LCC, this step is not foreseen and the results are expressed in terms of costs. In particular, they are expressed in terms of Net Present Value (NPV) using a discount rate of 3%.

For the social dimension, no impact assessment was carried out since only a social risk assessment could be performed. In this regard, the results are expressed in terms of the likelihood of a certain social issue occurring within a particular economic sector for a particular country. For the purposes of this study, only the social issues for which a “high” or “very high” risks are determined to be relevant. Given that in some instances the social risks in each of the economic sectors vary, a point scale was defined to assign the overall risk corresponding to a social topic. This point scale ranges from 7 points (very high risk) to 1 point (very low risk). Furthermore, 4 points were assigned when no data was available to ensure that missing information is acknowledged while avoiding over- or underestimations of risk levels.

2.5 *Interpretation*

For all sustainability dimensions the most relevant hotspots were identified. For the environmental dimension, the most relevant life cycle stages and impact categories were determined. Similarly, the most relevant life cycle stages and the most relevant cost categories are identified for the economic dimension. Finally, the most relevant social risks, identified as those marked as "high" or "very high" are listed. The results are subject to uncertainties that cannot be addressed here due to space constraints, including result variations due to different data sources (e.g., different databases), the choice of the impact assessment method in LCA; or the selected discount rate in LCC.

3 RESULTS AND DISCUSSION

3.1 *Life cycle assessment*

The most relevant environmental impact categories had a total contribution of 83.50% and are Resource Use, fossils (RU-f, measured in MJ) (33.30%), Ecotoxicity, freshwater (ET-fw, measured in Comparative Toxic Units – CTUe) (29.50%), and Climate Change (CC, measured in kg CO_2 equivalents) (20.70%). The characterized results for these impact categories are presented in Table 1.

Table 1. LCA results for the most relevant impact categories expressed per FU

Modules	CC [kg CO_2 eq.]	ET-fw [CTUe]	RU-f [MJ]
A1	1.26E+05	1.66E+07	8.50E+06
A2	3.67E+04	3.67E+05	4.79E+05
A3	1.62E+05	4.46E+05	1.69E+06
A4	3.75E+04	3.75E+05	4.91E+05
A5	3.56E+02	3.61E+04	1.03E+04
B2	2.24E+04	2.92E+05	3.88E+05
B4	3.82E+05	4.52E+07	1.34E+07
Total	**7.67E+05**	**6.33E+07**	**2.50E+07**

For all impact categories (including those not presented in Table 1), the most relevant life cycle stage is Module B4, with a contribution of 49.80%, 71.43%, and 53.77% for CC, ET-fw, and RU-f, respectively. The main reason for this is the great amount of raw material and energy used for the production of the mixtures needed for the replacement and rehabilitation activities. This conclusion is supported by the influence of Module A1 on the results, which is the second most influential stage in most impact categories, including ET-fw and RU-f. For CC, the second most relevant life cycle stage is Module A3. The least influential stage was Module A5, with contributions lower than 1% for most indicators. Furthermore, the influence of Modules A2 and A4 in the results varied, but was still considered to be relatively low, with contributions ranging from 0.58% (A2 for ET-fw) to 4.89% (A4 for CC). Based on these findings, the most relevant processes for the studied infrastructure and the defined system boundaries are related to raw material extraction and processing, as well as asphalt mixture production.

3.2 *Life cycle costing*

The NPV of the structure amounted to 4.08 Mio€ for the defined FU and system boundaries. A breakdown per life cycle stage is presented in Figure 2.

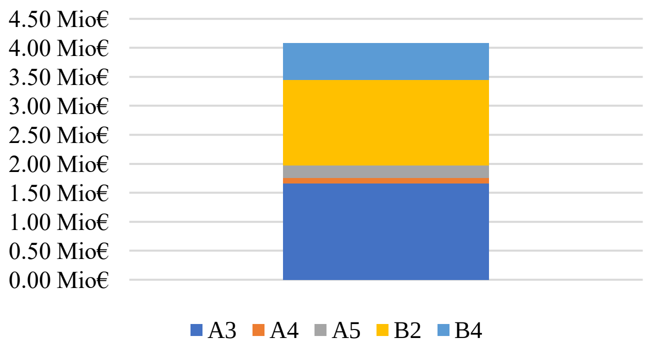

Figure 2. NPV per FU of the assessed pavement structure.

Two main contributors to the life cycle costs are highlighted: initial material costs (accounted for in Module A3) (40.83%), followed by maintenance activities (35.92%). Within Module B2, winter service produces the highest costs, contributing about 77.48% to this stage. In turn, Modules A2 and A5 contribute only 2.14% and 5.48% to the total costs, respectively.

In terms of cost categories, it is not possible to define a hotspot due to the nature of the different life cycle stage and the fact that in several cases, only lump sums could be used in the calculations.

3.3 *Social hotspot analysis*

Based on the approach described in Section 2.4, social risks were identified for the stakeholder categories of local community, value chain actors, and workers.

The topics of biomass consumption, international migrant stock and migration flows present high risks. Biomass consumption is significant due to ecosystem disruption and the need for extensive land clearance for the extraction of raw materials and the preparation of the construction site. Furthermore, many economic sectors in Germany rely increasingly on migrant workers, which could lead to increased risks related to discrimination, unfair working conditions and conflicts with the local community. Moreover, topics in relation to corruption, such as “active involvement of enterprises in corruption and bribery” and “anti-competitive behavior”, were also found to present a high social risk for all studied sectors. Further social risks identified are related to gender wage gap, fair salary, and trade unionism.

4 CONCLUSIONS

This contribution explored the use of LCSA in pavement through a case study, focusing on potentials and challenges of this method in the road construction industry. One prominent challenge is ensuring consistent system boundaries since different methods require different levels of detail in the assessment. Furthermore, access to primary data remains a significant hurdle, particularly for LCC and S-LCA, where even reliable secondary data is limited. For instance, while some resources such as Baupreislexikon exist for LCC, they showed large deviations when compared to representative data from the Autobahn GmbH. Similarly, while secondary databases exist for S-LCA, they may not account for all relevant stakeholders, affecting the completeness of the assessment. In this case study, social aspects connected road users (consumers) were not considered since they are not part of the scope of the used database.

Nonetheless, LCSA still offers several potentials. In particular, hotspots can be systematically identified, up to the level of processes and even elementary flows, allowing for reductions in sustainability impacts while avoiding burden-shifting among dimensions. Moreover, decisions based on the sustainability performance of the pavement can be made on a more holistic basis, considering the three dimensions of sustainability. Furthermore, this case study provides a methodological pathway of how LCSA can be applied for a road construction project, as well as shows existing limitations and how these can be dealt with. Further work could define LCSA benchmark values to compare the performance of a project to a reference, as well as to address sources of uncertainty in the assessment.

5 ACKNOWLEDGEMENTS

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