Towards environmental design decision-making for infrastructure planning using parametric BIM

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ABSTRACT: The AEC industry is responsible for 32% of the global greenhouse gas (GHG) emissions. The greatest potential to reduce the environmental impacts of infrastructure projects has been identified to be in the early design stages, where trailblazing decisions of the road corridor and the construction type must be made. We propose a methodology for an automated calculation of embodied and traffic emissions based on Building Information Models (BIM) of infrastructure assets. Our approach supports decision-makers in identifying optimal road corridors not only by means of design aspects but also by taking environmental impacts into consideration. Hence, we introduce predefined, parametric LCA profiles including cut-and-fill considerations, various road profiles, and structural assets like tunnels and bridges. The bill of quantities is automatically derived from the BIM model for the subsequent LCA calculation. Finally, the resulting GHG emissions of different routing variants can be automatically calculated and compared for holistic design decision-making.

1 INTRODUCTION & MOTIVATION

In terms of climate change and the scarcity of resources, it is necessary for the AEC sector to sufficiently evaluate and justify the decision-making for construction projects. In addition to building construction, this is also of utmost importance for infrastructure projects. For the continuous reduction of CO_2 emissions, the embodied and traffic emissions of different routing alternatives should be considered at an early design stage (Liljenström 2021, Sauer 2016).

For the calculation of the embodied and traffic emissions over the entire lifecycle, the methodology of life cycle assessment (LCA) is used. LCA is a standardized approach to calculate the environmental performance of products and processes and ”can be used to identify the highest points of concentration of emissions and analyze which actions can be taken to achieve their reduction more efficiently” (de Oliveira et al. 2021).

The greatest opportunity to reduce the environmental impacts of a road design is located in the early design stage where the choice of the road corridor and the construction type is made (Liljenström et al. 2021). However, the required information for conducting an LCA, such as the quantity of construction material, is hardly available and time-consuming to collect in an early planning stage. The relevant information becomes available in later design stages when fewer opportunities exist to reduce the environmental impacts.

A possibility to balance the conflicting objectives is the application of BIM methods to accelerate the time-consuming data collection and design evaluation of different routing alternatives. The BIM methodology shifts the design efforts into earlier design stages as semantic 3D models are developed and their relevant information is collected to conduct analyses. Therefore, the evaluation of different design possibilities can be conducted earlier where changes have greater effectiveness and possible conflicts can be resolved in time which improves the design quality (Borrmann et al. 2018).

The objective of this research is the development of an integrated evaluation system that provides end-users with a quick assessment of different routing alternatives by considering emissions caused by constructing and operating the infrastructure assets in question.

The rest of the article is structured as follows. Section 2 provides an overview of related research activities and motivates the identified research gap. Section 3 introduces the conceptual approach and elaborates on the assumptions made to implement a holistic yet flexible approach for LCA considerations in the early design stages of civil infrastructure projects. The proposed workflow has been tested in a case study, which is summarized in section 4. Section 5 concludes the findings and discusses future improvements.

2 BACKGROUND & RELATED WORKS

Currently, the environmental impacts of built assets are mostly considered within the framework of a rating system in the context of a sustainability assessment. The ecological aspects of sustainability are thereby determined with the help of an LCA. For example, a proposal for an indicator system by Schmellekamp (2016) evaluates the different sustainability aspects with a degree of fulfillment depending on a point system. Even though, no evaluation system for the sustainability of infrastructure projects has been officially introduced (Zinke et al. 2021).
Sustainability tools are mostly developed for end-product evaluation. The design phase must be completed to a certain extent in order to be able to carry out a sustainability assessment. However, decisions that have the highest impact on the environmental effects need to be made during the early design stages as the choice of the road corridor. For conducting an LCA for the choice of the road corridor, a simplified LCA is required (van Eldik et al. 2020). A European research project about Life Cycle Consideration in EIA of Road Infrastructure (LICCER) addressed this issue. They developed an LCA tool in Mircosoft Excel to calculate the annual energy use and related annual GHG emissions over the life cycle of the infrastructure project (Brattebø et al. 2013). However, it is still necessary to enter the data manually from the road model to the LCA model.
In a simplified LCA, traffic as well as embodied emissions should be considered. Traffic emissions are the emissions emitted by vehicles due to fuel consumption in the operation phase. Embodied emissions are associated with the life cycle of an infrastructure asset and include the construction, operation, maintenance, and demolition of the engineering constructions such as the superstructure of roads, bridges, and tunnels. According to Sauer (2016), the construction of a tunnel in mountainous regions might reduce GHG emissions as a smaller longitudinal gradient is achieved. The emissions from the reduced traffic will compensate for the higher emissions during the construction phase after several years.

The implementation of a BIM-based LCA has rarely been performed so far in infrastructure projects. The consideration of traffic emissions and the combination of road superstructures and civil engineering assets has not yet been carried out. In previous studies, only the embodied emissions were evaluated for different engineering constructions. Differences in previous studies exist in the functional unit, the consideration of different life cycle stages, different environmental indicators, and the integration process of BIM and LCA. Slobodchikov et al. (2019) and Maibaum & Block (2022) both conducted a BIM-based LCA for calculating the embodied emissions of the superstructure of a road. Van Eldik et al. (2020) evaluated the environmental impacts of a bridge in a cradle-to-grave consideration. As part of the Integbridge research project, a BIM-based LCA has been developed for steel bridges. In addition to the ecological aspects, the other two dimensions of sustainability are also taken into account (Zinke et al. 2022).

The literature overview has unveiled deficiencies in BIM-based LCA calculations that consider the construction process as well as the operation phase of infrastructure assets. Therefore, the next section introduces a comprehensive framework that aims to close the gap identified.

3 METHODOLOGY FOR ENVIRONMENTAL DESIGN DECISION-MAKING

The objective of our proposed methodology is the automated assessment of different routing alternatives regarding their environmental impact with the help of BIM models in the early planning stages. Thereby, the routing alternatives consist of the road corridor and engineering constructions such as bridges and tunnels. The overall structure is illustrated in figure 1.

In the first step, the LCA objectives, functional unit and system boundaries are defined as goal and scope. The functional unit of the conducted LCA is set as:

> GWP [kg CO_2 e] over the life cycle of 100 years of different infrastructure routing alternatives enabling traffic between the same start and end point.

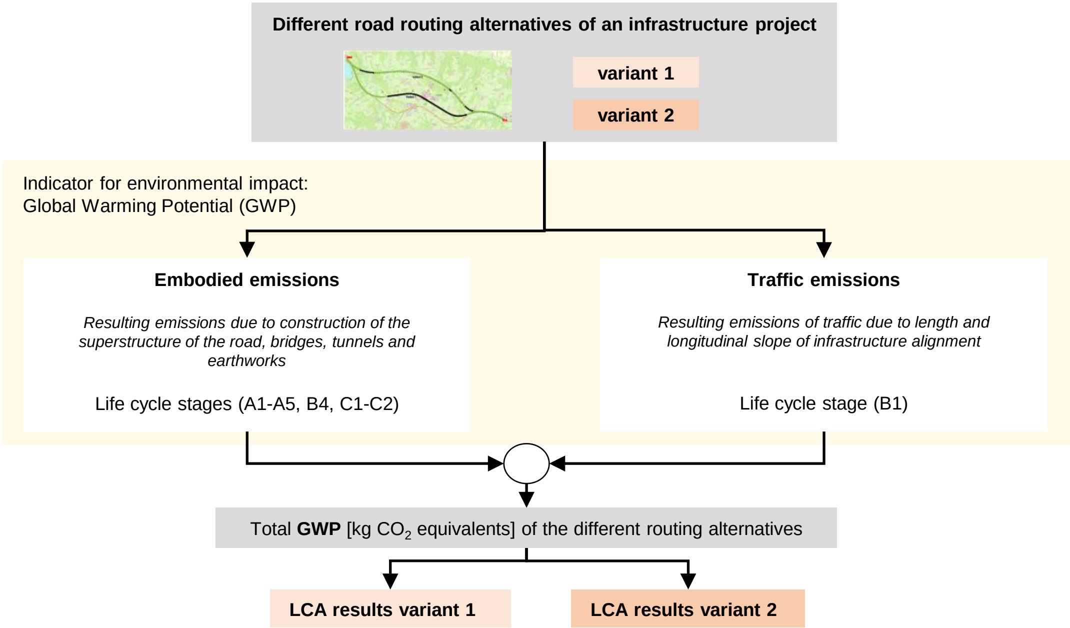

Figure 1. Defined goal and scope of the life cycle assessment.

Since engineering structures are designed for 100 years (EN 1990 2010), the same period is assumed here for LCA calculation. For the superstructure materials of a road, differentiated life cycles are accumulated over the period of 100 years. The different service life cycles depend on the type of material, which is divided into an asphalt and a concrete superstructure, and influence the replacement of components (B4) in the maintenance stage. For example, the service life for the top layer of asphalt superstructure is set to 10 years, and for concrete superstructure 60 years (according to Liljenström et al. 2021). As depicted in figure 1, LCAs are conducted for each routing alternative of a road infrastructure project. The global warming potential (GWP) is selected for evaluation as the environmental indicator. The indicator is evaluated for both, the embodied and traffic emissions of the infrastructure asset in question. To oversee the infrastructure project over its entire life cycle, the embodied emissions of the product stage (A1-A3), transport to site (A4), construction process (A5), replacement of components (B4), and end-of-life stage (C1-C2) must be considered in the calculation. The traffic emissions are relevant for comparison with the embodied emissions (Sauer 2016), and therefore included and assumed here as the use stage (B1) for infrastructure project. The final LCA result is the total GWP of each routing alternative created over the defined period.

3.1 *Proposed workflow*

In order to carry out a BIM-based LCA in an early planning stage, the parametric BIM models on the one hand and the predefined LCA profiles on the other hand are required. Their interactions are depicted in figure 2.

Due to existing uncertainties in early design stages, BIM models mainly consist of sparse information and typically include information about the envisioned axes, terrain information, and assumed cross sections that are positioned along the envisioned track. Furthermore, many design decisions in early project phases build upon standards and regulations that take the expected traffic load into consideration. These guidelines enable resilient assumptions about the overall shape of the road body, the number of lanes per direction, and the envisioned overall width of the road. Furthermore, the analysis of the terrain information provides the basis for the axis design including the horizontal and the gradient layout. Subsequently, supporting structures like bridges or tunnels can be placed accordingly and are included in the resulting BIM models at least in a low level of detail. After creating the BIM models, all information relevant to the subsequent LCA calculation is collected in the bill of quantities (BoQ). This includes, for example, the type of material such

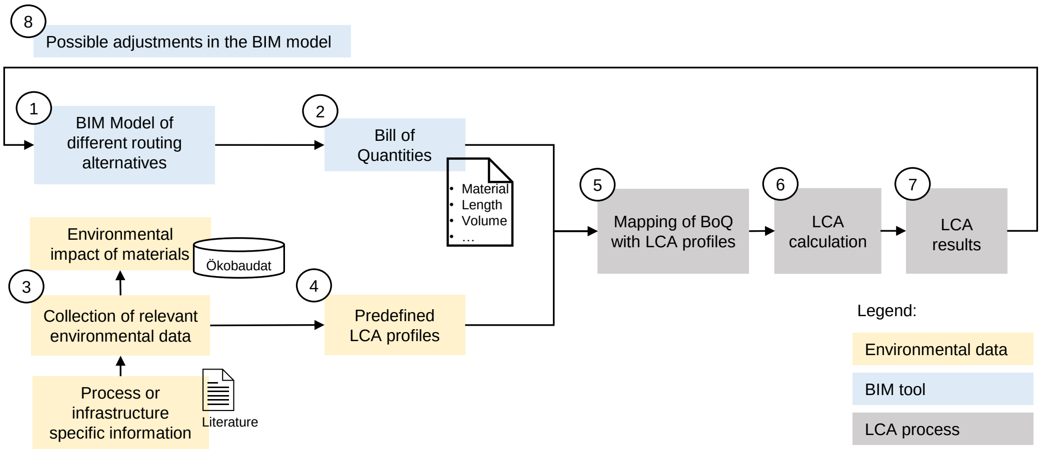

Figure 2. Overview of the proposed methodology including model preparation, calculation, result assembly, and impact evaluation.

as concrete or asphalt for the superstructure and the associated volumes of the different layers. In the next step, the BoQ is automatically mapped with the LCA profiles.

For compiling suitable LCA profiles, different kinds of sources are considered. The first and main source is the ÖKOBAUDAT which is a German database with verified data quality and uniform data formats (Brockmann et al. 2019). Unfortunately, the ÖKOBAUDAT does not provide all information relevant to the evaluation of civil infrastructure assets yet. Therefore, missing information, such as transport distances caused by the location of the construction site and environmental coefficients for fuel consumption must be gathered from other sources. These sources consist of results from different research studies, which are explained in more detail in the following subsection.

Finally, the LCA calculation can be conducted using the predefined LCA profiles and the information extracted from the BIM models. The calculation of the LCA (indicated as step 6 in figure 2) reports the GWP for each routing alternative (step 7). Depending on the results, the BIM model can be adjusted to optimize the routing alternative and iterate through steps 1, 2, and 5 to 8 until a sufficient design option is reached.

3.2 *LCA profiles for the early planning stage*

As outlined before, it is essential to choose suitable LCA profiles that are capable of representing environmental indicators for the different road features.

According to the data typically available in early-design BIM models, assumptions for the material choices and its specific service life cycles of the road superstructure must be taken. Furthermore, indicators for cut-and-fill considerations and engineering structures like bridges and tunnels are required.

For the superstructure of a road, the corresponding environmental indicators are compiled from the ÖKOBAUDAT for the life cycle stages A1-A3, A5, and C1-C2. For an asphalt superstructure, data concerning the different road layers are represented. However, the LCA data quality in the ÖKOBAUDAT for concrete road layers is incomplete. Therefore, it was necessary to compile different materials for individual layers. Since these were not available for all life cycle stages, a comparison at this point is not completely representative. Next to modules C3 and C4, data for the construction installation process (A5) of a concrete superstructure are missing.

In order to roughly estimate the GWP for the early planning phase of a tunnel, estimations developed by Sauer (2016) are utilized. These results in length factors (per tunnel meter) that depend on the selected standard cross-section and the type of excavation. Next to the construction, length factors for the annual GWP, resulting from the use phase, were determined. Thereby, a distinction is made between operation and maintenance. The emissions in the operational phase result from the electricity consumption for lighting and operating technology. Maintenance and servicing of the tunnel structure lead to emissions during maintenance.

The LCA profile for bridges contains area factors for the resulting GWP. These consist of an upper and lower limit value to address the level of uncertainty. As a lower limit, the assumption of Sauer is stored with a GWP of 1000 kg CO_2e/m^2 bridge area. For the upper limit, a reference value of 1370 kg CO_2/m^2 is applied which was determined in research projects for uniform sustainability criteria for infrastructure projects (Mielecke et al. 2016). The different life cycle stages are considered with a percentage share for production, maintenance, and end of life.

The amount of traffic emissions depends on the type of cross-section which determines the annual average daily traffic (AADT), the length of the route, and the type of vehicle. The latter is distinguished by car or truck, and both of them are powered by diesel or petrol.

The consideration of electric cars and the changing electricity mix are not part of this framework. In the LCA profiles, the GWP depending on the longitudinal slope for cars and trucks is stored. The associated factors are based on the assumptions of Fischer et al. (2012).

3.3 *Required data from BIM model*

For the proposed methodology, the information listed in table 1 needs to be extracted from the BIM model. It is distinguished between information needed to calculate the embodied and traffic emissions. For the embodied emissions, the BoQ is needed which includes mostly the geometric information as volumes and quantities of the construction project. Whether the length, area, or volume of the road structure element is needed, is determined by the associated unit in the LCA profile. To estimate the traffic emissions, the length sections with a continuous longitudinal gradient are required from the BIM model.

Table 1. Required information to extract from the BIM model.

	Required information from BIM model
Embodied emissions	Road corridor with its superstructure layers Volumes of the different layers Cut and fill volumes of road corridor Kind of road structure element Tunnel length and corresponding cross-section type Bridge area
Traffic emissions	Length sections Corresponding longitudinal slope

4 CASE STUDY, IMPLEMENTATION & RESULTS

4.1 *Prototypical implementation*

A prototypical implementation has been made using well-established software tools. The model preparation takes place in Autodesk Civil 3D (version 2022), where the BoQ and all other relevant information can be extracted using the visual programming application Dynamo for Civil 3D. In addition, the predefined LCA profiles prepared in Excel are imported into Dynamo and linked with the data of the BIM model. The subsequent calculation of the LCA is directly performed in Dynamo and its results are exported to Excel.

The use of existing LCA tools for the calculation process was not possible as not all of the necessary data is available there. Data concerning environmental indicators for tunnel or bridge construction are for example missing. Therefore, as suggested by van Eldik et al. (2020) and Maibaum & Block (2022), visual programming language (VPL) is used for the integration and calculation process. In case of new aspects to consider in the future, visual programming tools offer high adaptability.

4.2 *Case study project*

In order to validate the presented methodology and its implementation, a case study was carried out. The case study evaluates different routing alternatives located at the Irschenberg in Bavaria and its results can be partially compared and validated with those of Sauer (2016).
Within the framework of a master's thesis (Bracher 2010), several different routing variants of the motorway A8 in the area of Irschenberg were developed. The new variants should lead to a more optimal routing thus coping better with the considerable amount of traffic and reducing the number of accidents that occur.
Due to the difficult topography, there is a different need for engineering structures such as bridges and tunnels. In order to demonstrate the balancing of the GWP for tunnels, bridges, and roads, two variants are investigated in the following which is both adjusted to the same starting and end point. The alignment of the first variant mainly consists of a 4.3 km long tunnel that passes under the Irschenberg with a longitudinal gradient of 1%. Variant 2 consists of three bridges with a total length of 1.5 km additionally to the road corridor.

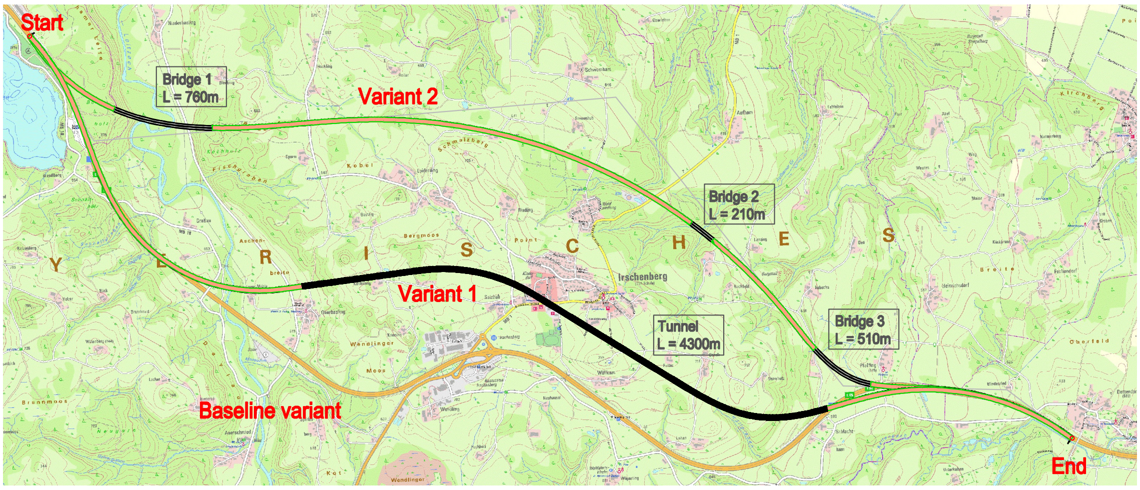

Figure 3. Overview of the case study project consisting of the different road routing alternatives.

4.3 *LCA results*

The LCA results are exported from Dynamo in an Excel file for each respective routing alternative. The results of the GWP-related emissions are provided in individual worksheets for the different infrastructure elements and the traffic emissions. A comparison over 100 years indicates the dominance of traffic-related emissions. The question arises, after how many years the embodied emissions are compensated by the relatively lower traffic emissions in comparison to the baseline variant. To assess this, the respective cumulative emissions of the different variants are considered over time. In order to assess the traffic emissions of the baseline variant, the results obtained by Sauer (2016) are applied. Exemplarily, only the results of the asphalt superstructure are presented in figure 4. More detailed results can be found in an extended version (Hofmeyer 2022). The emission results of each variant were calculated and visualized cumulatively over the construction life cycle period of 100 years considering all LCA stages, such as production stage (A1-A5), usage (B1) and maintenance (B4) and End of Life (C1-C2). The replacement effects of the LCA results are hardly visible due to the dominating traffic emissions.

The construction of the tunnel in variant 1 results in the highest embodied emissions which leads to the largest GWP of this variant after the construction is completed (year 0). The baseline variant starts with the lowest GWP as no construction measures were applied. Since the baseline variant yields the highest traffic emissions, this approach displays the steepest slope. As a result of the construction of variant 2 and the reduced traffic emissions, the point of intersection (PoI) with the baseline variant is already reached after 4 years. For variant 1, the intersection with the baseline variant occurs after approximately 19 years. With regard to the GWP, the construction

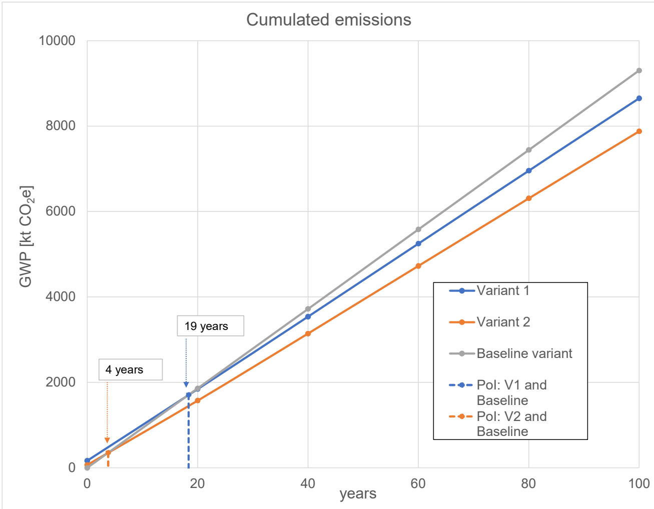

Figure 4. Cumulated emissions over a time period of 100 years of the different variants and its point of intersection (PoI) with the baseline variant.

of variant 1 or 2 is an improvement over the baseline variant. When comparing variants 1 and 2, variant 2 performs better, as both embodied and traffic emissions are lower.

5 CONCLUSIONS

In the early design stage, only limited information regarding the rough construction parameters of infrastructure projects is available and can be represented in the BIM model. Nevertheless, the choice of different routing variants has a big influence on the environmental impacts of infrastructure projects. Hence, we propose a methodology for an automated calculation of embodied and traffic emissions based on BIM models reflecting infrastructure assets. The LCA results of the applied case study confirm that traffic emissions are responsible for the largest share of the GWP over a lifespan of 100 years. Therefore, it is important to raise awareness in the construction industry that fuel-efficient construction of infrastructure projects can significantly reduce the GWP impacts.

Since the designs for engineering structures, such as bridges and tunnels, have not been detailed at that early planning stage, length factors depending on the required cross-section or area factors are applied for determining the embodied GWP emissions of engineering structures.

As the implementation has shown, all relevant information can be extracted from the BIM model, including the volume of the individual road layers, the cut and fill volumes, the area of the bridge structures, and tunnel lengths. The manual, time-consuming process of calculating the BoQ can thus be reduced in time and increased in quality simultaneously.

The limiting factor in the presented methodology is the missing datasets specifically for infrastructure materials and construction processes. While comprehensive indicators for building construction are already available in the ÖKOBAUDAT, this is unfortunately not the case for infrastructure components. For example, datasets for the different layers of a concrete superstructure are not sufficient or fully missing.

For the future, the presented methodology can be extended due to limitations, which were initially made in order to limit the scope of the present work. The scope of the performed LCA only considers the GWP as an environmental indicator. If the availability of other indicators gets better in the future, the scope can be extended accordingly. At the sustainability level, only the environmental aspects have been evaluated. However, the economical and social dimensions could be extended for a BIM-based decision-making process. Another limitation is the type of traffic mode as only roads have been considered so far. An extension for railway systems would therefore be feasible and is also highly dependent on sufficient LCA data. Therefore, the enrichment of standardized and officially validated life cycle databases for infrastructure projects should be aimed for. In addition to material-specific environmental impacts, more information regarding the lifespan of the materials and transport distances is required. Since the highest embodied emissions in road construction occur during the maintenance phase, the applied maintenance cycles and lifespans are of great consequence.

Another open research question considers the dynamic aspect of the LCA profiles and datasets. Different traffic scenarios, the development of fuel efficiency, and the share of electric, hydrogen, or petrol-powered cars lead to dynamic changes in the datasets rather than static ones. Data from the ÖKOBAUDAT should also vary over time, as different energy sources and mixes change dynamically, too. These changes will lead to a different ratio of embodied and traffic emissions but will give a more realistic prediction of the overall environmental emissions of infrastructure projects.

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