Resource indicator-oriented building information modeling for the management of infrastructure

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Abstract. This paper contributes to increasing resource efficiency by providing a method for calculating the environmental impact in the context of the infrastructure sector. For this purpose, the LCA method is linked to a parametric BIM model for road construction. Municipal existing road structures and characteristics were considered for the development of the approach. The research topic is motivated by the sector of infrastructure construction and especially road construction, which is enormously resource-intensive. Therefore, resource efficiency indicators such as raw material consumption, energy consumption and climate warming must be adequately implemented in the information model for the entire life cycle of a road construction project. The aim of this work was to combine the two areas of resource efficiency calculation and parametric BIM modeling and to generate added value from this combination. In this way, relevant indicators can be extracted that can also be used to define the information needs in terms of resource efficiency and further developed as recommendations for municipal operators. The extension of the methodology to other infrastructure areas has been identified as a further starting point. In the future, it must be ensured that resource flows are recorded holistically to increase resource efficiency.

1. Introduction

The construction sector is one of the most resource-intensive sectors and responsible for a considerable share of energy consumption, greenhouse gas emissions and the binding of highly demanded raw materials. Therefore, it is up to the construction sector to meet climate targets and reduce resource consumption of construction materials. The infrastructure sector, and especially the road sector, makes a significant contribution to this [1]. By taking a holistic view of the life cycle of construction materials, building procedures and structure types, the environmental impact can be quantified and measured. For this purpose, the integration of life cycle assessment (LCA) becomes obvious. The LCA is a structured procedure for providing information on environmental impacts within a defined scope of investigation. The complexity of the information to be processed varies with the scope of the investigation. To be able to evaluate more aspects, adequate digital support is required.

Despite the continuous progress of digitization and the application of the building information modeling (BIM) method in road construction, its dissemination is currently still limited. Furthermore, the integration of LCA into the BIM methodology is also still in the early stages [2].

This paper presents a methodology that performs automated LCA for parametric BIM model of road structures. The approach is intended to be applicable for municipal use. It considers a high level of model adaptability and parameterization, while it allows at the same time the recording of environmental impacts of road construction projects in a simple and transparent manner. Based on a given data structure used by a municipality, different parametric cross sections are created, extruded, and adapted. The parametric road models are linked to the assigned environmental impact data, which are retrieved from an open database. Meanwhile, the methodology is applied to different typical road superstructures and a comparison of route variants. For further model exchange and processing, a property set is automatically created, which links the relevant LCA and material data with the road model.

It can be assumed that in the future, the holistic consideration of environmental impact aspects will become increasingly relevant, especially for road construction projects. However, at present, there are neither BIM-integrated LCA tools nor a wide-ranging and reliable amount of environmental product declarations (EPDs) defined specifically for the infrastructure sector. Therefore, there is a high need for action and research in this area.

2. Resource efficiency and LCA in road design and construction

The literature section emphasizes the contextual aspect of resource efficiency in the road sector. The LCA implementation is described and relevant LCA databases and tools are presented. The last subsection highlights previous research that examines LCA regarding BIM.

2.1. Definition of resource efficiency

Resource extraction and use, and associated negative environmental impacts continue to increase globally [3]. Construction and demolition of infrastructure facilities account for 30 % of European resource use and waste generation [4]. Increasing resource efficiency would result in a significant reduction in consumption in all sectors of the economy [3]. In this context, resource efficiency means creating more (economic) value by using fewer resources while simultaneously reducing environmental impacts [5].

To be able to apply suitable measures to increase resource efficiency, this must be adequately quantified [5]. Multiple analysis methods exist for this purpose, such as LCA.

2.2. Implementation of the LCA

According to ISO 14040 [6] and ISO 14044 [7] the LCA methodology can be divided into a 4-step iterative process. This consists of defining the objective and scope, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation of the LCIA. The LCI includes the step of data collection. Here, all input and output flows are detected. The LCI represents the inventory of direct environmental impacts, waste generation and consumption of energy and raw materials. The LCI forms the basis for the subsequent LCIA step. In the LCIA assessment, the total recorded environmental impacts are categorized and characterized. The resulting indicator values are subsequently interpreted and evaluated.

EPD are based on the LCA and are a standardized format for presenting LCA results in a third-party verified and registered document. In Europe, EN 15804 provides the core product category rules for EPDs of products in the building sector [8].

2.3. LCA databases and tools

LCA data sets can be specified as the smallest modeling unit in a life cycle model. In the process, each of these datasets incorporates different in- (resources) and outputs (emissions and waste-products) [9]. Several of these datasets, also known as process units, are combined into one life cycle model. Data sets can be subdivided into cradle-to-gate, cradle-to-grave and cradle-to-cradle data collections [10]. This describes the individual product life phases. A cradle-to-gate dataset covers the environmental impacts from extraction to the end of production. Cradle-to-grave also includes the disposal of the product. cradle-to-cradle describes the possibility of returning the product to the use phase.

An LCI database is defined as a system used to organize, store, and easily retrieve large volumes of digital LCI records [11]. A database should provide comprehensive input/output flows for datasets, a consistent modeling approach and naming, and complete and consistent dataset documentation [10]. The aggregation of process and inventory takes place either individually or aggregated, depending on the database [12]. The EPD platforms with the most EPDs are EcoPlatform EPD, IBU, INES, the GaBi, ÖKOBAUDAT, Ecoinvent and the international EPD System [8, 12].

In general, several commercial and non-commercial LCA tools are available that can be used to determine the life cycle impact of road infrastructure. There is the British asPECT, the France ENCORCE-M and the American PaLATE tool for example. For the building construction sector, several BIM-LCA-tools like Tally and One Click LCA which attempt to take the BIM method into account are existing. For the infrastructure sector, however, this approach is still only feasible to a very limited extent. In particular, the non-transparent calculation methods as well as the lack of certain LC phases, the poor comparability and additional the less implemented EPD product range are to be seen as disadvantages [13].

2.4. LCA for road structures in the context of BIM

LCAs have traditionally been introduced and carried out for individual products. After progressively more complex interrelated systems such as a building were also subjected to an LCA, the area of infrastructure and in particular the road system increasingly moved into the focus of this approach [14, 15] . This usually involves the different life cycle phases of the road system - construction, use and maintenance. Balaguera et al. also show that the different phases make a significant contribution to the life cycle assessment of the road product [16].

The environmental impacts that can be cited are the change in the use of the land occupied, the destruction of the landscape, the erosion and slippage of soils and slopes, the input of pollutants, the alteration of the original, naturally occurring drainage patterns of water and, ultimately, the pollution of water, soil, and air. To be able to perform far-reaching analyses in this fields and to handle the information complexity, reliable digital tools are needed. In the construction sector, BIM is already being used, which is designed to present and manage a large quantity of building-specific information in a consistent and transparent way. Several papers already exist that examined LCA assessments in the infrastructure sector. The integration of LCA into BIM methodology has rarely been part of research in this sector [2].

van Eldik et al. mention the heterogeneous software landscape as a disadvantage leading to incomplete BIM models. It is noted that an explicit data structure for integrating environmental and BIM data is not provided at this time. Consequently, the potential in terms of interoperability and flexibility is not fully exploited. Finally, the lack of bidirectionality of data traffic and the insufficient application of environment impact assessment integration in the BIM process were assessed as limitations. The approach enables compare planning variants in a timely manner and provides the evaluation of decisions regarding environmental impacts efficiently [17].

The approach published by Forth et al. also aims at automation in the field of resource efficiency [18]. An optimized calculation option was developed, which determines LCAs faster, more consistently and more accurately in a semi-automated way through improved integration in BIM. Based on this, digital models that pay special attention to geometry and materiality have been investigated and modeling recommendations derived using the error analysis.

Röck et al. emphasized the significant impact of decisions made in an early design phase [19]. They recommend the usage of conceptual BIM models and visual scripts to investigate a variety of design-specific hotspots when conducting LCAs.

Slobodchikov et al. showed a simplified possibility of linking LCA calculations in the BIM methodology using a generic approach as an example [20]. Different LCA data were added to the road model and contrasted with a uniform LCA data set for the same road. The consideration of parameters such as the emissions of the construction equipment, the project uncertainties or the availability of data turned out to be a major challenge here.

By integrating LCA into the BIM methodology, different challenges can be addressed. The integration of these methods focuses on the digital and transparent quantification and calculation of environmental impacts, which leads to objective benchmarks [21]. Trunzo et al. showed that the maintenance and use phase has the most negative environmental [22]. Furthermore, Karlsson et al. used GIS, BIM and LCA data to assess the energy consumption and greenhouse gas emissions of road sections at the planning stage [23]. The adding of further digital tools such as aerial photography, material flows and storage can help to increase the efficiency of material use and to control its impact [24]. The approaches illustrate that taking environmental impacts and material factors into account in early project phases can have a positive impact on the robustness and longevity of a road structure and improve the overall balance.

To realize BIM-LCA integration Collao et al. suggest that visual programming tools such as Dynamo are predominantly and increasingly used [25]. In this context Wastiels and Decuypere present an overview to classify BIM-LCA integrations [26].

3. Concept of the BIM-based resource efficiency calculation

The proposed approach combines existing geometric information, material information, and environmental parameters in a parametric BIM road model using open databases with the goal of performing automated LCA as selected method for resource efficiency calculation.

For this purpose, the achieved workflow is explained in a first subsection. The second subsection described the technological basis.

3.1. Implementation of a BIM-based LCA Workflow

The aim is to combine the BIM methodology with resource efficiency calculations. Based on the data structure analysis of a municipal road database, a proposal for the optimal structure of road sections for semantic and spatial road query and evaluation was developed. It turned out that the existing data is incomplete, but generally all relevant data fields were provided by the operators. For the computation of environmental impacts based on a road information model, it is therefore essential that the characteristics are embedded in the modeling. During the flowchart-based creation of the parametric road cross-section, various property parameters and attributes are created. Furthermore, relations between different road construction components were defined, to ensure the parametric variability, especially when modeling and calculating an LCA of existing structures. An overview of the conducted workflow is provided in figure 1. The identification, analysis and processing of the input data is followed in the second step by linking to a parametric BIM model.

Road planning is based on the country-specific guidelines, in which the external circumstances (traffic load, share of heavy traffic, etc.) are considered. In the context of German infrastructure, the guideline RStO12 [27] is applied, which is used as the foundation for the parametric model in the use case. Figure 2 shows the parametric road cross section (bottom) based on the RStO12 guideline (top). For the transition from 2D cross section to 3D road model, the cross-sections are extruded axis based. As input for this, the existence of a digital terrain model is necessary. In addition to the longitudinal and cross-section, the exact axis course has to be included in the 3D road modeling. The applied property data sets are created in a way that they can also be controlled and manipulated. This is important for the subsequent LCA calculation. First, the data is imported from the databases described above in a script-based process. The subsequent calculation and linking of model data such as QTO, mass and volume calculation, and the environmental impact data such as $CO2$ emissions is carried out by means of a mapping

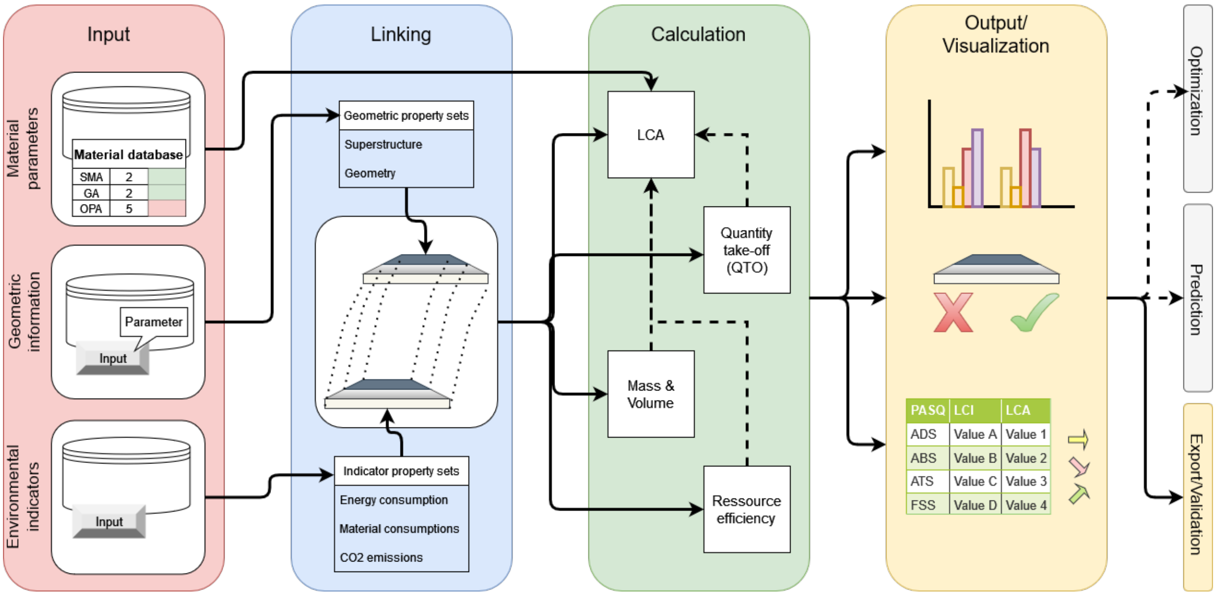


Figure 1: Overview of the process steps carried out in the created parametric infrastructure model analyze tool (PIMAT)

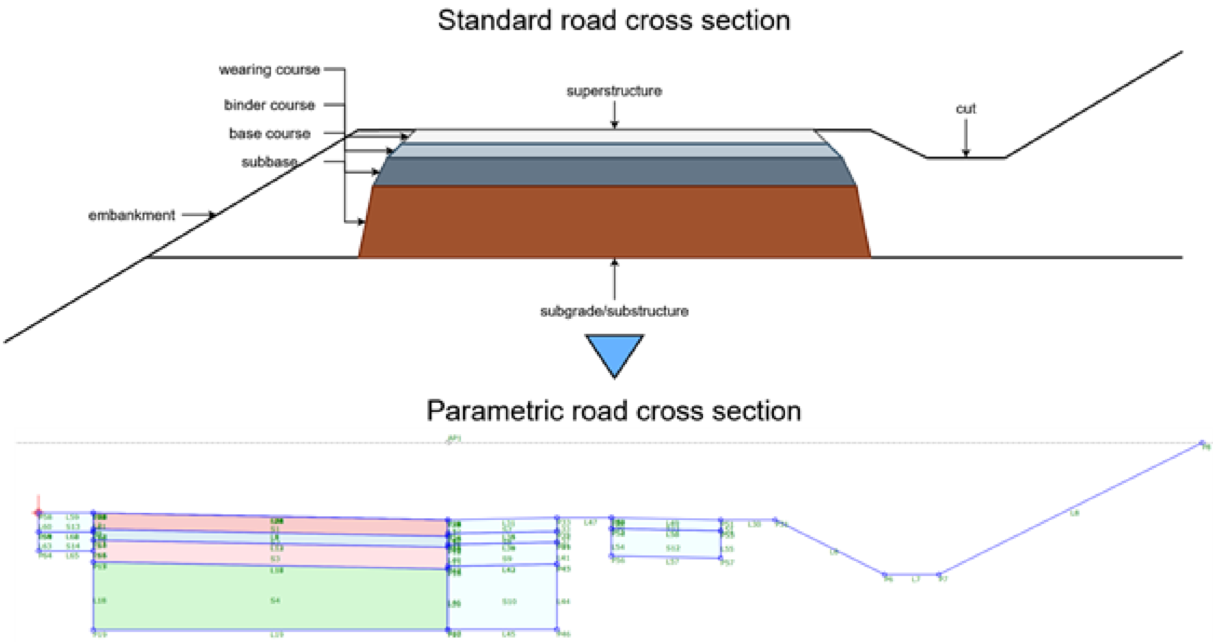


Figure 2: Based on the standardized and encountered dependencies and layer parameters within different road structures (top), the road cross section modeling was carried out (bottom).

algorithm (cf. figure 3). The process step of the LCA consists of the automated calculation of the life cycle inventory and the impact assessment based on it.

After the calculation of the relevant indicators raw material consumption, energy consumption and CO2 emissions for different use cases, the property data sets are filled with the LCA data in a further step. In addition to perform the LCA, it has also been shown that further resource efficiency criteria need to be considered. This includes, for example, the creation of condition forecasts for existing roads. Furthermore, the methodology created can be extended to other areas such as civil engineering with minimal effort. Via graphical user interfaces, the user can intervene at various points in the road information modeling process and LCA implementation and take special features into account in the planning phase. Non-guideline-compliant superstructures, which are common in municipal applications, as well as specially installed materials can be adapted for entire road sections as well as for partial sections.

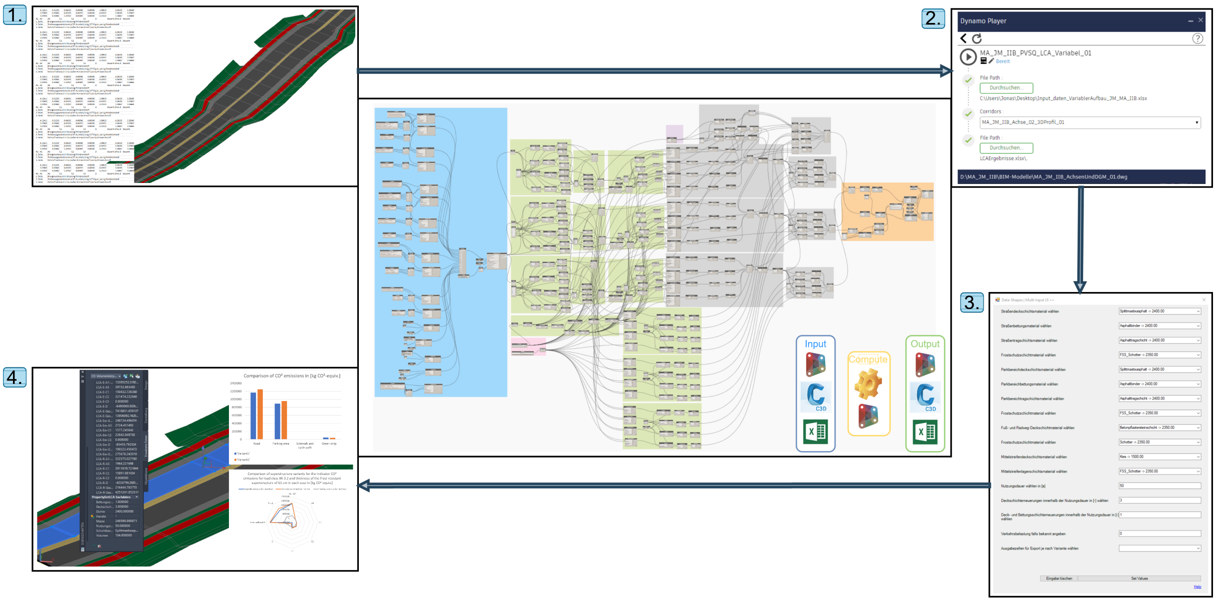


Figure 3: Process flow of the LCI and LCA calculation: (1.) Import of the model and the relevant environmental data sets; (2.) Start of the LCA calculation tool; (3.) Input of additional model information; (4.) Output of the calculated LCI and LCA data; In the middle of the figure the LCA script created by Dynamo can be seen.

3.2. Applied technologies for the BIM-LCA integration

For the parametric road information modeling and the subsequent LCA implementation, different digital tools, and databases are used. The geometric and semantic data derived from the road database QGIS were first analyzed and processed. The same was done for the data collected from the German environmental product database ÖKOBAUDAT. It contains over 1200 EPDs and makes the data available in a machine-readable form. The database offers a standardized programming interface (API) for the direct exchange of data. Other applications and software tools can use this interface to read data records from ÖKOBAUDAT. The data records are identified by a unique identification number (UUID).

From the 2020 NBS National BIM Report, Autodesk products are the predominant choices for BIM applications with 70 % market share. For this reason, inter alia, the Civil 3D road planning software was primarily used for the modeling [28]. Multiple road cross-sections are created by using the Subassembly Composer which is implemented in the Autodesk Civil 3D. In the following step, the Civil 3D was used for the 3D road modeling, which is based on the 2D road cross-sections. The Dynamo plug-in was used for automated parameterized model creation and LCA implementation. This visual programming tool can be used to access a wide range of model parameters and attributes and to integrate external data sources. Through the implementation of geometric and mathematical operations, both life cycle inventory data and impact assessment data were determined transparently in the LCA implementation step. In a final step, relevant LCA data were linked to the model by means of dynamo application. Due to the current lack of an adequate API integration, the data sets have been imported and exported to Excel.

4. Use case: Comparison of different alignment options and road structures

To verify the methodology, different prototypical use cases have been carried out. This was done to achieve the highest possible adaptability of the road information model on the one hand and a transparent and automated model generation and LCA implementation on the other. For this purpose, an existing digital terrain model was used. Various typical road structures have been compared with each other. Furthermore, the methodology has been applied to different alignment options. In this way, resource-intensive road sections can be identified at an early planning stage and potential measures, changes in the planning or recommendations can be derived on this basis. The figures 4 and 5 illustrate the results for the two scenarios described.

Variant 1	Asphalt construction method			
Axis length: 1634 m; Cross section width: 13 m (15 m with bankett)				
Layer information	Wearing course (road)	Binder course (road)	Base course (road)	Subbase (road)
Layer thickness in [cm]	6	4	12	43
Density in [kg/m³]	2400	2400	2400	2350
Volume in [m³]	2541.85	1906.39	1906.39	5601.33
Mass in [kg]	6100434.56	4575325.92	4575325.92	13163120.70
Duration of use in [a]	50	50	50	50
Renewal wearing course in [-]	3	3	3	3
Renewal binder course in [-]	1	1	1	1
ÖKOBAUDAT material in [-]	Splittmastixasphalt	Asphaltbinder	Asphalttragschicht	FSS_Schotter

Variant 2	Asphalt construction method			
Axis length: 1506 m; Cross section width: (15 m with bankett)				
Layer	Wearing course (road)	Binder course (road)	Base course (road)	Subbase (road)
Layer thickness in [cm]	6	4	12	43
Density in [kg/m³]	2400	2400	2400	2350
Volume in [m³]	2706.70	2030.02	2030.02	6076.72
Mass in [kg]	6496069.37	4872052.03	4872052.03	14280287.79
Duration of use in [a]	50	50	50	50
Renewal wearing course in [-]	3	3	3	3
Renewal binder course in [-]	1	1	1	1
ÖKOBAUDAT material in [-]	Splittmastixasphalt	Asphaltbinder	Asphalttragschicht	FSS_Schotter

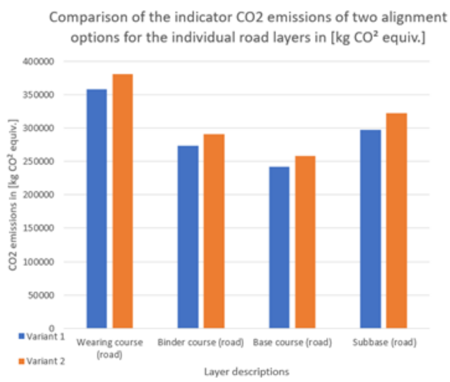


Figure 4: LCA data comparison for two alignment options (right: comparison of the calculated CO2 values of the individual road layers per alignment option)

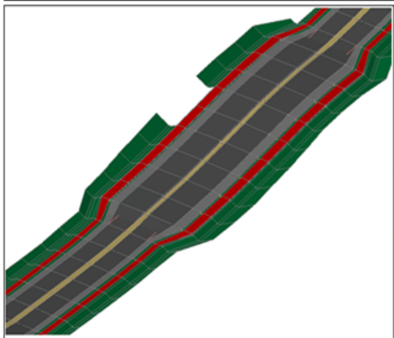
Figure 4 lists the data calculated during the LCA for the different life cycle phases of an asphalt road pavement in tabular form. In addition, the network diagram compares the asphalt, concrete, and pavement types for the indicator CO2 emissions. A cut-out of the road information model also demonstrates the high level of model adaptability that has been implemented. Figure 5 illustrates the life cycle inventory comparison of two different alignment options, which are additionally visualized in the lower section of the figure. The bar chart compares the individual layers of the respective alignment option. In general, changes to the digital model can be visualized easily and LCA data can be updated quickly.

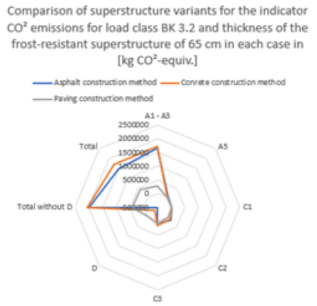
5. Conclusion, limitations, and further work

This paper intends to present a method, preferably automated, to support the holistic consideration of environmental impact aspects in road construction. For this purpose, a method for automated BIM-LCA integration using parametric road models were developed.

In general, a high degree of automation in the process of BIM-based road modeling and LCA execution has been achieved by creating numerous Dynamo scripts. These can be executed sequentially in the Dynamo Player environment. In addition, the reduction of manual input points and input constraints in the GUIs can reduce potential sources of error.

Holistic comparison of different environmental indicators for different road structures (in this case: asphalt, concrete and pavement structure)





Asphalt construction method

Calculation values			LCA with ÖKOBAUDAT data sets							
Layer	Indicator	Unit	A1 - A3	A5	C1	C2	C3	D	Total without D	Total
ADS	Energy consumption	MJ	22859448.44	59070.12	223645.46	477929.59	0.00	-9648648.79	23620093.61	13971444.82
	CO²-Emissions	kg CO² Äquiv.	469744.79	4050.39	2344.86	33661.50	0.00	-127045.49	509801.54	382756.05
	Raw material consumptio	kg	73076.76	9.86	5801247.06	79.80	0.00	-5702884.42	5874413.49	171529.07
ABS	Energy consumption	MJ	25195182.08	67866.23	297834.32	636470.94	0.00	-12849349.94	26197353.57	13348003.62
	CO²-Emissions	kg CO² Äquiv.	500559.72	4653.84	3122.71	44827.88	0.00	-169189.70	553164.15	383974.45
	Raw material consumptio	kg	667832.87	3355.25	7743216.78	31461.97	0.00	-7988293.66	8445866.86	457573.20
ATS	Energy consumption	MJ	18791446.68	58366.89	288976.79	617542.44	0.00	-12467213.14	19756332.79	7289119.65
	CO²-Emissions	kg CO² Äquiv.	443931.74	4001.94	3029.84	43494.70	0.00	-164158.04	494458.23	330300.19
	Raw material consumptio	kg	625381.81	2885.47	7512935.24	30526.29	0.00	-7750723.59	8171728.82	421005.23
FSS	Energy consumption	MJ	1726645.13	0.00	8929.03	34360.93	207231.81	-134451.31	1977166.90	1842715.59
	CO²-Emissions	kg CO² Äquiv.	252633.64	11333.26	11333.26	43905.63	115671.47	-35324.00	434877.25	399553.25
	Raw material consumptio	kg	1774798.58	0.00	7996.91	30766.62	492712.98	-87192.14	2306275.09	2219082.95

Concrete construction method

Calculation values			LCA with ÖKOBAUDAT data sets							
Layer	Indicator	Unit	A1 - A3	A5	C1	C2	C3	D	Total without D	Total
BDS	Energy consumption	MJ	7988362.87	82369.46	188333.24	733109.25	418799.19	-1571971.62	9410974.01	7839002.39
	CO²-Emissions	kg CO² Äquiv.	922706.47	4550.33	13061.14	50559.26	25321.76	-90164.01	1016198.97	926034.96
	Raw material consumptio	kg	261405.29	59.66	13.80	53.73	10112038.39	-10307851.37	10373570.87	65719.50
VS	Energy consumption	MJ	1041069.48	0.00	0.00	438.49	8104.46	-355242.58	1049612.44	694369.86
	CO²-Emissions	kg CO² Äquiv.	27912.07	0.00	0.00	30.83	41702.10	-18876.62	69645.01	50768.39
	Raw material consumptio	kg	304.01	0.00	0.00	0.07	13449.55	-13420.48	13753.63	333.15
HGT	Energy consumption	MJ	23999293.33	74542.64	369063.59	788687.66	0.00	-15922366.72	25231587.22	9309220.50
	CO²-Emissions	kg CO² Äquiv.	566962.64	5111.03	3869.53	55548.79	0.00	-209652.66	631491.99	421839.33
	Raw material consumptio	kg	798699.63	3685.15	32799.04	38986.33	9562265.13	-9898752.99	10436435.27	537682.28
FSS	Energy consumption	MJ	3995858.10	0.00	130361.94	501491.93	1709254.89	-486574.80	6336966.86	5850392.06
	CO²-Emissions	kg CO² Äquiv.	202900.64	9102.21	9102.21	35262.45	92900.59	-28370.18	349268.11	320897.93
	Raw material consumptio	kg	1427292.91	0.00	6444.42	24793.66	16062867.22	-12039798.38	17521398.21	5481599.83

Pavement construction method

Calculation values			LCA with ÖKOBAUDAT data sets							
Layer	Indicator	Unit	A1 - A3	A5	C1	C2	C3	D	Total without D	Total
PDS	Energy consumption	MJ	1263520.24	0.00	0.00	0.00	0.00	0.00	1263520.24	1263520.24
	CO²-Emissions	kg CO² Äquiv.	146985.37	0.00	0.00	0.00	0.00	0.00	146985.37	146985.37
	Raw material consumptio	kg	617013.26	0.00	0.00	0.00	0.00	0.00	617013.26	617013.26
PBS	Energy consumption	MJ	215297.27	0.00	40462.34	155655.38	530526.42	-151025.33	941941.41	790916.08
	CO²-Emissions	kg CO² Äquiv.	12235.33	0.00	2825.19	10944.92	28834.91	-8805.67	54840.36	46034.69
	Raw material consumptio	kg	127902.27	0.00	2000.25	7695.57	4985666.86	-3736968.19	5123264.95	1386296.76
HGT	Energy consumption	MJ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CO²-Emissions	kg CO² Äquiv.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Raw material consumptio	kg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FSS	Energy consumption	MJ	2544838.75	0.00	83023.50	319384.74	1088571.71	-309884.48	4035818.70	3725934.22
	CO²-Emissions	kg CO² Äquiv.	129221.16	0.00	5796.92	22457.56	59165.52	-18068.09	216641.16	198573.07
	Raw material consumptio	kg	908998.82	0.00	4104.25	15790.32	10229944.60	-7667776.17	11158837.99	3491061.83

Figure 5: LCA data comparison for three different road structure types (Top left: contrast of the calculated CO2 values of the individual road structures per life cycle phase)

To evaluate the created methodology, it can be stated that the presented work provides a possibility for transparent modeling of parametric road bodies and for efficient calculation and integration of environmental indicators into the BIM cycle. The prototypical implementation of the presented workflow showed that the municipal inventory data on which this use case is based is inconsistent and incomplete. Thus, manual preparatory work and additions were necessary at this point.

Currently, the method is limited by an EPD palette that is only rudimentary for the infrastructure sector. A uniform scheme for integrating LCA data into the overall sustainability assessment of an infrastructure project is also lacking in Germany. Furthermore, software manufacturers have actual partially implemented options for appropriate exchange in open data formats regarding to LCA data.

In the long term, infrastructure needs to be designed and built more sustainably, which means that approaches towards digital sustainability analysis such as LCA gain in importance. Existing infrastructure must also be sustainably refurbished and deconstructed. To accomplish this, as-built data must be continuously included into the analysis. Therefore, it is necessary to know and cover systematically the information needs of sustainability analyses. In this context, the use of an open data exchange format, such as the Industry Foundation Classes, is essential as it enables different stakeholders of an infrastructure project to work in a collaborative, transparent and holistic manner. Moreover, data consistency and quality are ensured by defining information exchange requirements

The heterogeneous software and road database landscape represents a particular challenge for municipalities. In summary, it can be stated regarding public administrations that it will be important in the future to identify improvement possibilities in detail. The basic prerequisite for directive compliant LCA implementation is the availability of representative data, which must be comparable in terms of time, geography, and technology. For this purpose, it must be demonstrated how (1) the structure of the infrastructure data can be optimized, (2) which data must be collected and to what level of detail, and (3) that the consideration of resource efficiency parameters must take place continuously.

In addition, in further steps, the BIM model can be extended to include other infrastructure components such as sewers, pipelines and other traffic areas. This makes sense to ensure a holistic view of the overall municipal infrastructure.

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