Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Element approach for BIM-based life-cycle modeling of bridges

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ABSTRACT: In order to establish a sustainable bridge assessment within a practical planning routine, it is necessary to reduce the calculation effort by applying automated algorithms. Information generated by the application of Building Information Modeling (BIM) can be used as project-specific input data for this purpose. For the method of life cycle assessment (LCA), the approach of linking the materials of the BIM-model with environmental data sets to calculate the ecological impacts has become widely established. This material-based approach provides sufficiently accurate results for an ecologic assessment in late planning phases. For early planning phases it is not directly applicable and the approach is not transferable to the application of the calculation methods life cycle costing and macroeconomic cost calculation.

The approach presented in this paper introduces a framework that can be used to calculate the life cycle impacts of a bridge by linking the objects of a BIM-model with the content of a hierarchically structured catalogue of elements. To establish this catalogue, individual items are pre-balanced and combined to generate base elements. To represent the entire life cycle of a bridge, follow-up elements, which occur after a specific time interval within the use and dismantling phase, are additionally defined. The individual base elements are combined into generalized major and macro elements into which the individual base elements are included with statistical shares. By applying the different element types, it is possible to use BIM-bridge models with different levels of detail for a holistic assessment and to include all impacts that occur during the complete life cycle.

1 INTRODUCTION

The sustainability assessment of bridges requires the application of different assessment methods. Some methods are based on qualitative and subjective evaluations and are therefore difficult or impossible to automate. For some quantitative assessment methods, Building Information Modeling (BIM) can be used to (partly) automate the calculation procedures and therefore reduce the manual effort significantly. This reduction is necessary to implement sustainability assessment as a method in everyday infrastructure planning. For life cycle assessment, a material-based approach using the volumes of BIM-objects and multiplying the derived material quantities with environmental impact datasets has been implemented in several software products. This paper discusses the shortcomings of such material-based approaches and introduces an element approach which can be used to calculate life cycle costs, ecological impacts and macroeconomic costs.

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2 SUSTAINABILITY ASSESSMENT

In the following, the methodological principles and standards for the quantitative methods of life cycle assessment, life cycle costing and macroeconomic costing are shortly described. For these methods the element approach can be used to calculate the impacts of a bridge using data generated by Building Information Modelling as project specific input data.

2.1 *Life cycle assessment*

Life cycle assessment (LCA) is a method for quantifying the potential environmental impacts of product systems over their entire life cycle. The calculation is standardized since 1996. DIN EN ISO 14040 (2021) and DIN EN ISO 14044 (2021) provide the methodological basis. A specification for the building product level is made in DIN EN 15804 (2022). Framework conditions at the building level are given in DIN EN 15643 (2021). The calculation methodology is specified for buildings in DIN EN 15978-1 (2021) and for infrastructures in DIN EN 17472 (2022). All material and energy flows within the specified temporal and spatial system boundaries must be recorded by default to fulfill the requirements of the standards. This surveyed life cycle inventory is translated into a life cycle impact assessment using characterization factors. As a result, the potential environmental impacts within different impact categories are provided.

2.2 *Life cycle costing*

Life cycle costing (LCC) is a method for quantifying the costs incurred within firmly defined system boundaries for a product system. The method is standardized by DIN EN 17472 (2022) and ISO 15686-5 (2017). Costs that occur during the use phase and dismantling phase are discounted to the year of construction using a discounting rate.

2.3 *Macroeconomic costing*

Most construction, repair and maintenance measures on bridges result in an impact on traffic flow. Due to construction sites the capacity of adjoining roadways is reduced. This leads to traffic jams and therefore large time losses, especially on highly frequented routes, for the general public. In addition, the emission of pollutants from cars increases significantly in a stop-and-go mode of driving. All mentioned effects can be monetized which means that impacts are transferred into monetary units. For example, time lost due to traffic disruption can be monetized by a macroeconomic hourly rate. As a result, the calculated macroeconomic costs can be compared with the direct construction-related costs. It is noticeable that these macroeconomic costs can exceed the direct building-related costs by a far extend (Zinke 2016). The calculation is part of whole-life costing (WLC) according to ISO 15686-5 (2017) and DIN EN 17472 (2022). The calculation rules for different impact categories are based on state-of-the-art descriptions in different national and international studies, for example Axhausen et al. (2014).

2.4 *BIM-based life cycle analysis*

Most existing calculation approaches within a BIM-based sustainability assessment use a material-based methodology (Alvarez Antón & Diaz 2014) and they mainly refer to the method of life cycle assessment. The calculation process is normally designed as follows: The BIM-model is transferred from the authoring software to an environmental assessment software via an IFC-interface or a plug-in. In the environmental assessment software, an environmental product declaration (EPD)-dataset is assigned to each geometric BIM-object based on the assigned materials in the BIM-model. The selection should always be checked manually. The multiplication of the EPD-datasets with the material quantity of the geometric objects delivers the result in the single environmental impact categories.

An assessment applying a material-based approach leads to sufficiently accurate results in later planning phases for calculating the ecological impacts of the main materials used to erect a bridge. However, if the entire life cycle is to be considered, the problem arises that building materials used in different elements possess different service lives and undergo different measures during the life cycle. The concrete which is part of a bridge edge beam, for example, is renewed on average every 33 years, while the concrete of the abutment survives the 100-year service life of a bridge. Accordingly, an assignment of specific life cycle measures to single materials is not appropriate.

Sustainability analyses in early phases can creates great benefits as in this phases the greatest leverage for influencing the later impacts exists. However, BIM-models, especially in early planning phases, do not have the necessary level of detail for an analysis on a material basis. For example, connection details are usually not modelled within the design planning. Corrosion protection systems are often not represented as geometric objects at all and are therefore they are not considered in the material-based methodology.

Furthermore, depending on the selected system boundaries and calculation methods used, the material-based methodology can result in significant inaccuracies. This can be explained at the example of corrosion protection systems. While for LCA focusing on building products (equivalent with the modules A1-A3 defined in DIN EN 15643) the neglect of the materials used in the corrosion protection systems is partly understandable due to the relatively small quantities of coating. Significant effects arise in the energy-intensive application of coatings (A5), as well as the repair measures (B2) and renewal processes (B4, B5) during the life cycle. For the methods life cycle costing and macroeconomic costing, these components cannot be neglected due to the costly scaffolding and significant traffic disruptions.

3 ELEMENT APPROACH

The element approach comprises that instead of focusing on materials, elements are used for the different life cycle-oriented assessment methods. These elements consist of all the items needed to fully compose an element. As an exemplary element the organic corrosion protection for steel beams is described. For this element, different items consisting of materials (e.g. coating materials) and processes (blasting the surface, coating the surface, etc.) are used. For all items, the resulting costs, environmental impacts and traffic impacts are pre-balanced.

3.1 *Considering different levels of detail*

In early planning phases and sometimes also in later planning phases shear studs or coatings are normally not represented in BIM-Models as specific geometric objects. To enable an analysis in early planning phases, pre-balanced items are added to base elements which are combined to major and macro elements (see Figure 1). The quantities of the pre-balanced base elements are allocated in the major and macro elements with statistical shares.

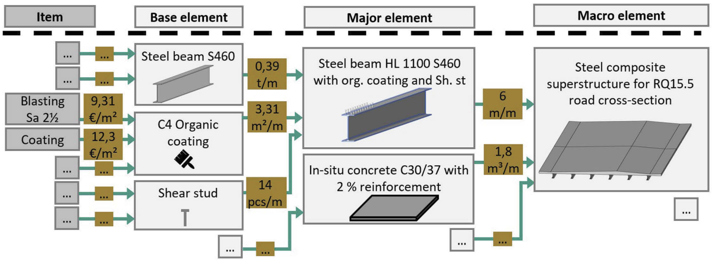

Figure 1. Composition of base, major and macro elements using statistical shares (Müller 2023).

The workflow foresees that macro elements and major elements (depending on the detailing of the BIM-model) are used in early planning phases. Accordingly, results can already be created in early planning phases in which all non-modelled components are represented by statistical shares in the composed elements. In the course of planning, the major and macro elements are replaced by base elements and thus the statistical shares are replaced by project-specific quantities which increases the accuracy of the calculation (see Figure 2).

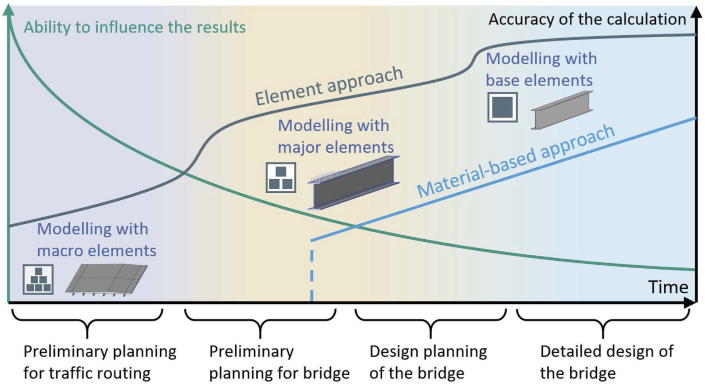

Figure 2. Life cycle dependent usage of different types of elements mapped with the corresponding accuracy of the calculations.

3.2 *Life cycle maintenance measures*

Base elements represent all bridge construction parts containing all potential impacts occurring in the production and erection phase. In order to represent all measures during the use and dismantling phase, follow-up-elements are defined. Follow-up elements, like base elements, are composed of pre-balanced items, but only occur after a maintenance strategy-dependent time interval during the life cycle. In order to represent different measures, a distinction is made between measure specific types of follow-up elements. Maintenance and repair elements are elements, that occur during the service life of a base element. Selective dismantling and renewal elements occur after the underlying base element has reached the end of its service life. Once the service life on a structural level has been reached, a dismantling element occurs which represents the demolition of the complete structure. Figure 3 illustrates the interactions of base and follow-up elements.

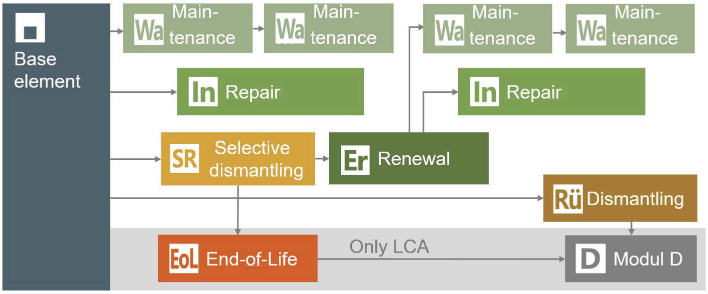

Figure 3. Interaction between base elements and follow-up elements (Müller et al. 2023).

4 LINKED BIM-MODEL APPROACH

All pre-balanced items as well as the base, major, macro and follow-up elements are stored in an element-database. To additionally use BIM-models as input data for calculations, the pre-balanced elements must be linked to the geometric objects of the BIM-model. An automated assignment based on the materials is not possible, because firstly, the elements are sometimes composed of several materials and secondly, elements made of the same material can have completely different properties (costs, degree of traffic impact, service life). An example is described above for edge beams and abutment concrete.

For an automated linkage of BIM-objects with base-elements, the IFC-classes could be used. Thus, based on the entity IFCBEAM with IFCBeamtype: Edgebeam, it can be determined that a linkage to an element "edgebeam" has to be established. However, it cannot be completely automatically determined whether for the calculation a base element (only the edgebeam) or a major element (edgebeam with sealing and curbstone) should be used.

In order to enable a mapping between the BIM-objects and the element-database, each pre-balanced element of the element-database is given a unique label. This unique label must be attributed to every BIM-object that is modelled in the authoring software. How the attribute is integrated into the BIM-model is workflow dependent. The labels of all available elements can be exported from the database as a classification file and loaded into a BIM authoring software. Here, the elements can be linked to the BIM-objects depending on the level of detail. The next step is the transfer of the attributed object with its quantities into a software for impact calculation which is labeled here as evaluation software. In the evaluation software the quantities of the BIM-models are combined with the specific impacts of the different elements to calculate the economic, ecological and macroeconomic impacts of a bridge (see Figure 4).

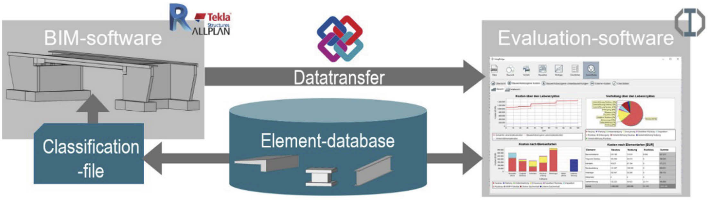

Figure 4. Workflow to use a BIM-model for a holistic evaluation.

5 CASE STUDY

The presented framework is exemplarily implemented using a steel composite bridge. To reduce the complexity for this paper only one steel girder is covered in this case study. The evaluation takes place during the comparison of different bridge variants and uses a BIM-model with the appropriate level of detail (no explicitly modeled connection details).

5.1 *BIM-model classification*

To use the BIM-model as input for a sustainability calculation, each geometric object must be linked to a pre-balanced element of the database. This can be done, for example, via the classification manager in the authoring software Revit (see Figure 5).

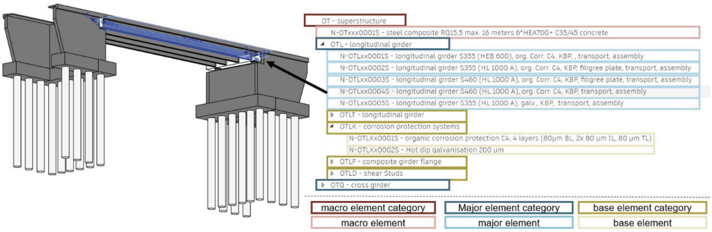

Figure 5. Assigning a label to each BIM-object for the holistic evaluation in the authoring software Revit.

Depending on the level of detail of the model, a major or fine element must be selected for the assignment. Since in this case the corrosion protection system and the shear studs are not modelled, a major element "*Longitudinal girder S460 HL 1000A, with organic coating C4 and shear studs*" is used.

5.2 *Calculation of impacts*

To use the classified BIM-model for a sustainability assessment, an evaluation software as explained and prototypical implemented in (Müller et al. 2023) has to be used. When the IFC-File with the linked BIM-objects is transferred to the evaluation software, the corresponding sub-elements and follow-up elements with their corresponding items are loaded from the element-database into the evaluation software automatically. In this case a beam with the length of 36 meter was assigned with the label for a major element. In the evaluation software this steel beam is split up into 119 m² organic coating, 504 shear studs and 14 tons of steel profile (see Figure 6).

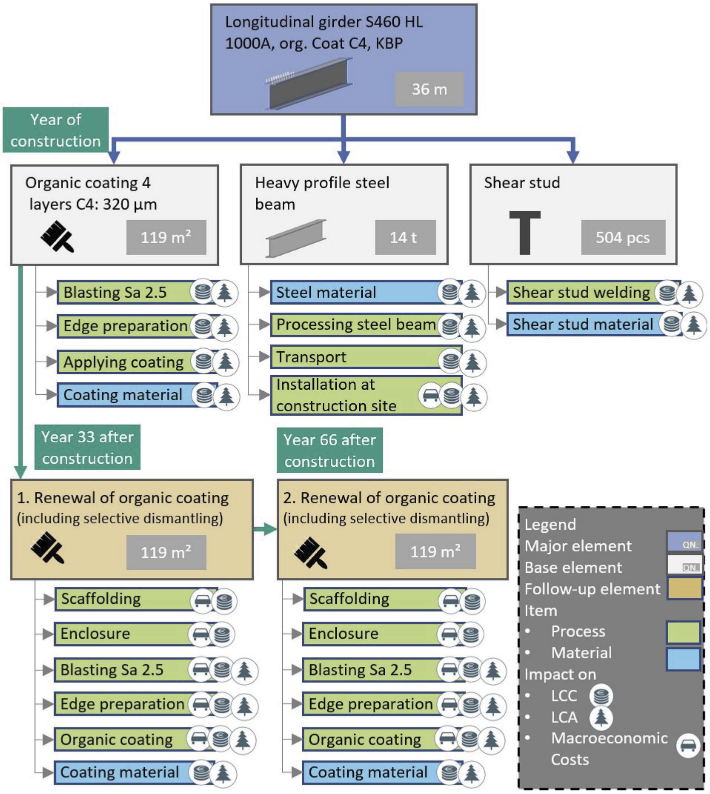

Figure 6. Elements and items used to calculate the impact of one steel beam.

For the steel profile and shear studs no measures occur during the complete life cycle of the bridge. The organic coating only has a service life of 33 years. Therefore, in the year 33 and 66 the selective dismantling and renewal elements of organic coating for 119 m² are used for the calculations. Each element consists of process and material items which can have an impact on LCC, LCA or macroeconomic costs. For example, the "Blasting SA 2.5" and "Applying coating" of the base element organic coating have an influence on LCA and LCC but not on macroeconomic costs since the coating is applied inside the production plant and therefore no traffic disruption occurs during the production. For the renewal of the organic coating the traffic must be disrupted and therefore these items lead to macroeconomic costs.

5.3 *Comparison of results*

Macroeconomic costs cannot be calculated when applying a material-based approach. For life cycle costs, the material-based approach is also generally not applied due to the poor interrelation between costs and pure material quantities. Nevertheless, this approach is often used for a BIM-based life cycle assessment. The deviations that arise with this approach compared to the introduced element approach are shown in the following.

When applying the material-based approach, the weight of the steel beam is multiplied with the values of a corresponding EPD-dataset. For the subsequent calculation the average data set for open rolled sections in Germany is utilized (bauforumstahl 2018). Therefore, the steel beam of 14 tons create a Global Warming Potential of 15.795 tons CO_2-eqv. (see first row of Table 1).

For the element approach, the same emissions result for the material of the steel beam. In addition, minor emissions for the welded head plate and end anchorage result in 0.175 t CO_2-eqv. The emissions for the 504 head bolt anchors lead to 0.280 t CO_2-eqv.

For the production of the organic corrosion protection system, emissions for the steel girder amount to 1.906 t CO_2-eqv. This results in additional emissions of 15% in the manufacturing phase. The major difference arises within the use phase. Bridge steel girders and head bolt anchors usually reach the 100-year service life. The corrosion protection must be replaced twice during this period. This results in high costs due to the required scaffolding and enclosure during the execution of the measures, as well as in high ecological impacts due to the energy-intensive blasting and application of the renewed coating. The ecological impacts for the renewal of the organic coating are higher than the ones of the initial organic coating applied in the production plant, due to the lower efficiency and higher overspray content of the processes on the construction site. In this case study, the emission calculated with a material approach underestimates the emissions by 30 % due to the neglected coatings and measures within the use phase.

Table 1. Comparison of LCA impacts calculated with a material and element approach.

Element	Quantity per functional unit	Year of Con. [t CO_2-eqv.]	Year 33 [t CO_2-eqv.]	Year 66 [t CO_2-eqv.]	Total [t CO_2-eqv.]
Steel beam (material approach)	14 t	15.795	-	-	15.795
Steel beam with shear studs and org. Coating (element approach)	36 m	18.161	2.169	2.169	22.498
- Steel beam with processing	14 t	15.970	-	-	-
- Shear Studs	504 pcs	0.283	-	-	-
- Organic coating production	119 m²	1.906	-	-	-
- Renewal of organic coating	119 m²	-	2.169	2.169	-

6 CONCLUSIONS

The introduced element approach allows to support a BIM-based sustainability assessment in different planning phases. Especially in early planning phases, in which an assessment can lead to major changes of the design, the element approach facilitates to create meaningful results. This is in particular the case when the underlying BIM-model do not have a level of detail with which a precise quantity takeoff can be performed. With an element approach, only the actual modeled content can be taken into account for an assessment and therefore the calculated potential impacts will be regularly underestimated.

6.1 *Limitations*

To apply the element approach to a specific structure, the corresponding elements and their items must be pre-balanced for all components of which the bridge consists of. This requires large preparatory works. In addition, the required items for an element depend on many boundary conditions. For example, a huge difference regarding the results of the macroeconomic costs calculation arises depending on the chosen construction process. If the corrosion protection system on a valley bridge is renewed using a hanging scaffold, the traffic below the bridge is not disturbed. If for a motorway overpass a standard scaffold is applied, a partial closure of the lower roadway is necessary. Accordingly, two different elements must be pre-balanced for the same organic corrosion protection under different boundary conditions and stored in the element database. Users must consider for which boundary conditions the elements were pre-balanced when assigning a label to an element in the BIM-model.

6.2 *Further steps*

For a large-scale implementation, many elements must be pre-balanced representing different bridge types, different spans and different construction processes. All pre-balanced results must be kept up to date. Especially for costs a yearly update should be provided. This can be realized by using accounted and already realized bridge projects as input for the database. Ecologic background data as well as input for macroeconomic cost calculation can be update within a longer period (2 to 3 years). The continuous support should be ensured by implementing a foster home.

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