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A data-driven parametric tool for under-specified LCA in the design phase

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Abstract. Life Cycle Assessment (LCA) is increasingly applied to evaluate the environmental performance of buildings. However, current tools for building LCA require detailed information not available in the decisive early design stages. As a result, LCA is usually applied as post-design evaluation and not used to improve the building design. The goal of this paper is to adapt the method of structured under-specified LCA to the Swiss context and implement it in a design-integrated tool. The users of the tool should be able to get a complete estimation of the life cycle impact based on very few inputs, such as building type, intended use and structural system. In addition, the tool should allow to replace these assumptions with more detailed information step by step throughout the design process. The paper describes the development of a structured database and a parametric tool. Furthermore, it exemplifies the intended workflow during the design process on a building design. The presented approach can be scaled up and adapted to the needs of other national contexts in the future. It facilitates environmental performance optimisation of buildings and supports making use of the big potential the building sector has regarding contributing towards climate action (UN SDG 13).

1. Introduction

According to the latest Sustainable Development Report of the year 2019 [1] most industrialised countries perform well regarding the overall Sustainable Development Goal (SDG) Index. Especially the Nordic countries are ranked high, with Denmark 1st, Sweden 2nd, and Finland 3rd. Norway is ranked 8th, followed by Iceland on rank 14. Switzerland is on rank 17. However, none of these countries perform well with regards to SDG 11 Sustainable Cities and Communities and even worse regarding SDG 13 Climate action. While some countries e.g. Switzerland and Sweden are on track to achieve SDG 11 by 2030, no country has implemented enough measures to be able to reach SDG 13. This clearly shows the high demand for action.

The built environment has the largest potential for delivering long-term, significant and cost-effective greenhouse gas (GHG) emission reductions [2]. Until now, the efforts to reduce GHG emissions mainly focused on the use phase of buildings. These measures have successfully reduced the operational energy demand for new and existing buildings and the limits for energy optimization in the use phase have mostly been achieved [3]. Therefore, the whole life cycle of buildings has to be evaluated. Life Cycle Assessment (LCA) has become a widely accepted method for environmental assessment of buildings in a scientific context but is still not commonly applied in design practice. In the rare case that it is applied, LCA is used as post-design evaluation as a mandatory part of sustainability certification schemes. However, post-design evaluation through LCA is not sufficient on its own, as it does not improve the environmental performance of the design [4].



In general, decisions made in the early stages of the design process, have the greatest influence, as they set general conditions for the subsequent design process [5]. As such, the early design phase has the highest influence on costs [5], operational energy demand [6] and environmental impacts [7]. Therefore, the biggest potential for optimization and reduction of GHG emissions lies in the early stages of the design process. LCA needs to be applied in early design stages to allow for holistic environmental optimization of the building.

One challenge to use LCA in early design stages is missing data. Many design decisions, for example regarding materials, have not been taken yet. However, current tools require detailed information to be able to calculate the environmental performance. To cope with missing or non-detailed information different approaches for under-specified LCA have been developed [8]–[11]. Tecchio et al. [9] develop a hierarchical structure for building assemblies based on the MasterFormat® and exemplify the method on a wall element. Cavalliere et al. [11] show the application of such an approach throughout the design process for a residential building using a theoretical case study. Hester et al. [10] use an algorithm called Building Attribute to Impact Algorithm [12] to optimise a building towards costs and environmental impact in early design stages. These recent developments show that the approach works for expert users and scientific case studies. However, currently no tool for building LCA can make use of structured under-specification throughout the design process.

The aim of this paper is to develop a parametric and design-integrated tool for LCA based on structured under-specification based on a Swiss LCA database. The users of the tool should be able to get a complete estimation of the life cycle impact based on very few inputs, such as building type, intended use and structural system. In addition, the tool should allow to replace these assumptions with more detailed information step by step throughout the design process. As such, it aims to provide continuous design feedback corresponding with the design stages and the decisions taken.

2. Structured under-specified LCA

The concept of structured under-specified LCA as used here, uses LCA data for materials and aggregates them on higher levels. In this paper, four of these levels are used: 1) Building, 2) Element, 3) Component, 4) Material.

The structure of the Swiss cost calculation (eBKP-H SN 506 511) is used (see Table 1). A building consists of eleven elements, such as exterior wall, roof, or technical equipment. Each element is made of one to five components. The element exterior wall consists of three components, for example. These are exterior wall finishing (including insulation), loadbearing structure, and interior finishing. The components are also the basis for defining the reference service life (RSL) according to SIA 2032 [13]. Each component is made of several materials. A reinforced concrete component consists of certain percentage of concrete and reinforcement for example, while an ETICS system consists of an insulation layer, plaster and paint.

If a layer of a material is under-specified, assumptions are used to approximate the missing information. If the thickness of the reinforced concrete wall and the percentage of reinforcement are missing for the exterior wall during the design of a single family house, for example, it can be assumed that the thickness will be between 16 and 20 cm and the reinforcing percentage will be around 2 vol%. As such, the LCA result can be calculated and a range of results can be provided. In this current version, the mean values and the minimum and maximum values are used. In the future, a distribution could be used to also output the probability. On a higher level of aggregation, the approach uses assumptions, too. If the user specifies that the building will be a single-family house with a minimum energy standard required by law and made of concrete, the elements that fulfil these requirements will be selected and the mean value and a range is output as result. In order to allow for this aggregation, a structure database of components and elements is needed.

Table 1. Structure of building elements and components

Building element	BKP-H Component
1. Base slab	C1 Base slab, foundation G2 Floor covering
2. Exterior wall under ground	C2.1A Exterior wall under ground E1 Exterior wall finishing under ground
3. Exterior wall above ground	C2.1B Exterior wall above ground E2 Exterior wall finishing above ground G3 Interior wall finishing
4. Window	E3 Window
5. Interior wall	C2.2 Interior wall G3 Interior wall finishing
6. Partition wall	G1 Partition wall G3 Interior wall finishing
7. Column	C3 Column
8. Ceiling	C4.1 Ceiling G2 Floor covering G4 Interior ceiling/roof finishing
9. Balcony	C4.3 Balcony
10. Roof	C4.4 Roof F1 Roof covering G4 Interior ceiling/roof finishing
11. Technical equipment	D1 Electric equipment D5.2 Heat generation D5.3 / D5.4 Heat distribution and delivery D7 Ventilation equipment D8 Water (sanitary) equipment

2.1 Structured Database

The Swiss building component catalogue (Bauteilkatalog) [14] is used as a basis for the structured database. Several categories are used to describe the building with a few input parameters in the earliest design stage. Each category provides several options. An overview of the categories in the database are shown in Table 2. Each category is described in the following.

Table 2. Categories for structured database

1 Height	2 Use	3 Energy standard	4 Material
Low rise	Residential SFH	Minimum	Concrete
Mid rise	Residential MFH	Above standard	Masonry
High rise	Office	Passivhaus	Timber
			Steel

2.1.1 Height

This category mainly influences the dimensioning of the structural components. Therefore, the width of the building is not relevant, but three different heights are used to describe the building. *Low rise* includes buildings up to 11 m in height which usually equals up to 3 stories. *Mid-rise* describes building up to 30 m in height or between 4 and 8 stories. *High rise* is used for building with more than 30 m or more than 9 stories.

2.1.2 Use type

The use type mainly influences the energy demand und the boundary conditions for the calculation of the operational energy demand. Currently, three categories are used: *Residential single-family house*

(SFH), residential multi-family house (MFH), and office. In the future, other types of usage could be added.

2.1.3 Energy standard of the envelope

Three choices for the energy standard of the external envelope are provided. *Minimum* defines the minimum requirements according to SIA 380. *Above standard* describes current state of the art of low energy buildings. *PassivHaus* uses the requirements needed to receive a Passivhaus certification. The u-values are shown in Table 3.

Table 3. U-values for energy standards

Elements	U-value in W/(m ² K)		
	Minimum	Above standard	PassivHaus
Opaque (external walls, roofs, floors)	≤0.2	≤0.17	≤0.15
Transparent (windows, doors)	≤1.3	≤1.0	≤0.8

2.1.4 Construction system and main materials

The fourth category defines the construction system and main materials used. Four categories concrete, masonry, timber, and steel are provided. These refer to the main structural system but include different materials. For example, a single-family house of the category masonry can have ceilings made of concrete. The masonry wall could be made of hollow bricks or aerated concrete bricks. These specifications will be added in later design stages. Based on the height of the building and the main material, the components with enough load-bearing capacity are selected. For instance, a high rise building in concrete will have a higher percentage of reinforced steel and thicker wall than a SFH. Currently, the selection is based on estimations without a structural dimensioning and factors such as seismic loads.

2.2 LCA calculation

The concept of parametric LCA [15] is used to develop a parametric LCA model. The geometry is defined using a 3D model of surfaces, similar to a thermal model. The model includes, ceilings, balconies, etc. that might not be needed for calculating the energy demand but are necessary for calculating the embodied impact.

The primary energy demand and environmental impact of the building are combined in the term *impact* for simplification. It distinguishes between the *operational impact* (I_O) resulting from the operational energy use of the building (life cycle module B6 according to EN 15978 [16]) and the *embodied impact* (I_E) resulting from production and the end of life of the building (modules A1-A3, C3, and C4). The replacement of building components (module B4) is also considered as I_E . The *life cycle impact* (I_{LC}) is the sum of I_E and I_O (see Equation 1).

$$I_{LC} = I_O + I_E \quad (1)$$

2.2.1 Embodied impact

The embodied impact (I_E) is calculated by multiplying the mass of each material (M_j) by the specific *embodied impact factor* of the material ($IF_{E,j}$) (see Equation 2). To determine the mass, first of all, the areas of the different building element surfaces have to be calculated. The surface areas are then multiplied by the thickness and density of the specific material. The density is imported from the KBOB database *Ökobilanzdaten im Baubereich* [17] together with the specific IF_E . Furthermore, the number of replacements (R_j) is considered. In this way, the I_E of every component is calculated and summed up to obtain the I_E of the entire building.

$$I_E = \sum_j (M_j \times IF_{E,j} \times (1 + R_j)) \quad (2)$$

For some materials, such as windows, the KBOB database provides the I_E per surface area of the element. In this case, the element area A_j can directly be multiplied with the I_E .

$$I_E = \sum_j (A_j \times IF_{E,j} \times (1 + R_j)) \quad (3)$$

To calculate the number of replacements (R_j), the reference study period (RSP) is divided by the reference service life (RSL) of the building component. The RSP for residential buildings is 60 years in Switzerland. The RSL is defined in SIA 2032 [13]. R is calculated according to equation 4. For example, if a painting possesses an RSL of 20 years, it must be renewed twice within an RSP of 60 years, so R equals 2.

$$R_j = \lceil RSP/RSL_j \rceil - 1 \quad (4)$$

2.2.2 Operational impact

The operational impact I_O consists of the sum of all different kinds of *operational energy demand* during the use phase (ED_i) multiplied by the *operational impact factor* of the energy carrier ($IF_{O,i}$) (see Equation 5). ED refers to the *final energy demand* and is calculated with reference to one year of operation. Therefore, the sum is multiplied by the number of years of the reference study period (RSP). The operational impact factor (IF_O) depends on the energy carrier employed and is taken from the KBOB database.

$$I_O = \sum_i (ED_i \times IF_{O,i}) \times RSP \quad (5)$$

The ED is calculated according to Swiss standards. The calculation approach is described in SIA 380/1 [18]. The ED consists of space heating, hot water demand and electricity demand for appliances and lighting. The standard uses a quasi-steady state monthly energy balance to calculate the space heating demand. The monthly values are summed up to the annual value and added to the warm water demand to provide ED for heating. The simplified approach of SIA with fixed global values for the hot water and electricity demand is used.

The results of SIA 380/1 are the useful energy demand of a building. To account for different kinds of losses within a building and for the performance of the selected heating source (e.g. heat pump or gas-condensing boiler), the performance factor (PF) is used. The PF is introduced to describe different types of building services with one systematic approach. To calculate the final energy demand, the useful energy demand is divided by the PF. The ED can also be calculated using other tools for building performance simulation, e.g. Honeybee/Energyplus, and manually input.

The impact factors ($IF_{O,i}$, $IF_{E,j}$) depend on the indicators chosen for the LCA. Equation 7 shows $IF_{O,i}$ and $IF_{E,j}$ for the indicators used by the Swiss KBOB database for building materials. UBP stand for *Umweltbelastungspunkte* or *eco points*, a single score indicator based on the Swiss *Method of Ecological Scarcity* [19]. The primary energy demand is provided as renewable part (PER) and non-renewable part (PENr). Furthermore, Global Warming Potential 100 (GWP) expressed in CO₂-equivalent as indicator for climate change is used as defined by IPCC [21].

$$IF_{O,i} = \begin{pmatrix} UBP \\ PENr \\ PER \\ GWP \end{pmatrix}, IF_{E,j} = \begin{pmatrix} UBP \\ PENr \\ PER \\ GWP \end{pmatrix} \quad (6)$$

3. Design-integrated tool

The development of the tool for structured under-specified LCA is based on the current version of Bombyx [22]. Bombyx is designed and implemented as a plug-in for Grasshopper, an add-on Rhinoceros 3D. The plug-in is free and available at Food4Rhino¹. The project is open source, so users can download the whole source code from GitHub².

¹ The latest version of Bombyx and example files can be downloaded from: <https://www.food4rhino.com/app/bombyx>

² GitHub source: <https://github.com/Bombyx-ETH/Bombyx>

3.1 Database

The material and component data used in Bombyx is stored in a SQL database. In addition to the LCA data, physical properties such as thermal conductivity are saved with the materials. In the future, further properties could easily be added. The categories defined above are added on component and element level to allow to filter the elements, components, and materials. The filtering occurs on different levels. If the material type timber is specified, only materials that belong to this category are used for example. If a Passivhaus standard is selected, only exterior walls with a u-value equal or below 0.15 W/(m²K) are used.

3.2 Workflow

The workflow is exemplified by a case study. The building is modelled in Rhino using surfaces only. The surfaces are assigned to predefined layers corresponding with the eleven elements (see Figure 3). The predefined Grasshopper script reads in the area and orientation of these surfaces to generate a thermal model and calculate the bill of quantities. In the Grasshopper viewport, the specification of the materials and the technical system is done. On the building level, only the four inputs height, use, energy standard and main material are needed (see Figure 1). This provides all necessary information for the calculation of the embodied impact, but also the operational impact. For example, if the energy standard PassivHaus is selected, the tool filters the exterior walls that match the u-value of 0.15 or below. The u-value is mostly influenced by the thickness of the insulation layers in this case. For an ETICS system on a masonry wall, this would mean 24 cm of EPS insulation, for example. Based on the filtering, the average values of all construction that fulfil this criterion will be retrieved from the database.

If the building should be specified in more detail in later design stage, the next level can be added. On the element level, more details for every element can be specified (see Figure 2). This will apply more detailed filters, narrowing down the potential solutions and therefore providing a smaller range for the LCA results. The way to output the results stays the same. Following this approach, a component level can be added and finally a material level, to specify each material explicitly and have a final, deterministic LCA result.

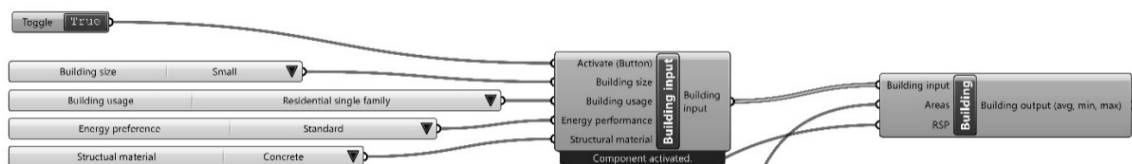


Figure 1. Simplified input on building level

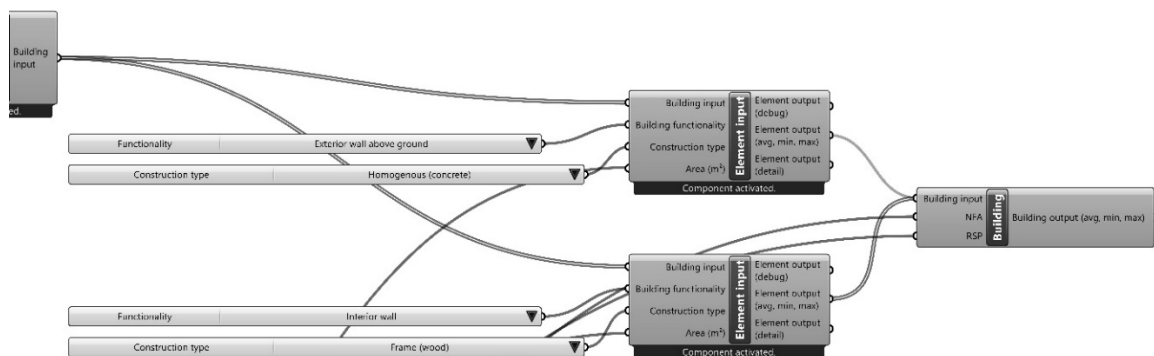


Figure 2. Simplified input on element level

The results are given out in the Rhino viewport. Next to the numerical results, visualisations are shown (see Figure 4). A scale visualises the absolute performance based on benchmarks provided by Hollberg et al. [23]. The colour coding of the building elements in the 3D model shows the performance of the selected elements compared to the available options in the database. This can support users in identifying optimisation potentials regarding the embodied impact.

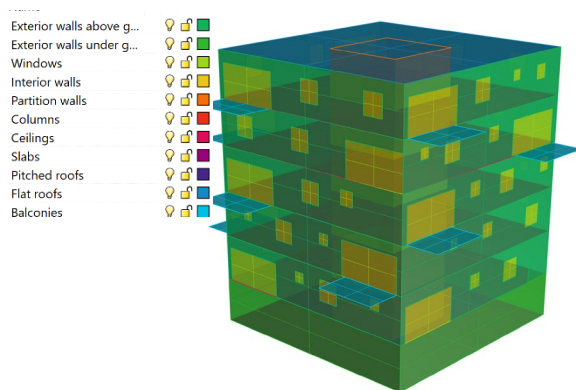


Figure 3. Input of geometry via color-coded layers

GWP embodied
kg CO₂-e/(m² a)
4.71

GWP operational
kg CO₂-e/(m² a)
4.81

GWP life cycle
(kg CO₂-e/(m² a))
0.794

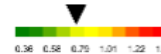


Figure 4. Visualisation of results (including total GWP and GWP per building component)

4. Discussion

This paper describes the implementation of structured under-specified LCA in a parametric design tool for the Swiss context. The database used to filter and give out under-specified design options is based on the Swiss Bauteilkatalog [14] using most typical building components in Switzerland. This will be sufficient for state-of-the-art constructions, but does not allow to integrate novel, innovative solutions into the assessment. As such, the building component catalogue and the structured database should be extended continuously. In addition, further properties should be integrated into the material catalogue, allowing to connect further analysis methods to the under-specified workflow, e.g. daylight or Life Cycle Costing (LCC). Further, categories can be introduced to allow for more accurate predictions of the LCA results.

The tool was developed to allow for the application of LCA in the crucial early design stages to indicate optimisation potentials at a time when major design changes are still feasible. Previous implementations of the parametric LCA approach showed that students were able to save about 16% of GHG emissions throughout the building's life cycle compared to their initial design variant [24]. Furthermore, it was shown that their design caused about 30% less GHG emissions compared to a reference group that did not use such a tool during the design process. This shows the big potential of integrating simplified LCA for design optimisation into early design stages. Further case studies with practicing architects will be needed to confirm this potential.

Currently, the tool has been developed for Switzerland using Swiss data. Nevertheless, the method is applicable globally and can be easily scaled up. The basic requirement is a database with LCA data on building materials. Besides Switzerland, other countries develop national databases, e.g. ökobau.dat in Germany. In addition, Environmental Product Declarations (EPDs) can be used to establish a database.

5. Conclusions

This paper showed the implementation of a structured under-specified LCA approach into the design process using a tool within the parametric design environment. Using a structured database pre-calculated LCA values for typical building components in Switzerland, allows for quick feedback regarding environmental impacts over the whole life cycle in every design phase. From just defining four input parameters in the first building level, to finally defining each material, the approach makes sure that the LCA is calculated as accurately as possible in each stage. The presented approach can be scaled up and adapted to the needs of other national contexts in the future. It facilitates environmental performance optimisation of buildings. As such, it supports making use of the big potential the building sector has regarding contributing towards climate action (UN SDG 13).

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