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A METHOD FOR EVALUATING THE ENVIRONMENTAL LIFE CYCLE POTENTIAL OF BUILDING GEOMETRY

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Abstract
Life Cycle Assessment (LCA) is becoming more and more important for building sustainability evaluation. However, in architectural practice LCA is not carried out in early design stages although the consideration of the environmental life cycle performance (LCP) is essential for creating sustainable buildings and early design stages offer the highest potential for optimization. The main focus in these design stages lies on the definition of the building geometry. However, conducting an LCA only based on building geometry is impossible due to missing information about materials and HVAC systems. Therefore, in this paper we propose a method for assessing the potential LCP (PLCP) that a building geometry offers. PLCP describes the probability of a specific building geometry to achieve a certain LCP in later design stages. This measure can serve to optimize designs according to life cycle aspects. The application of the method is exemplified for the evaluation of six geometric variants of a residential building. The results indicate that PLCP is a valuable measure for decision-making in the architectural design process.

Keywords:
Life Cycle Assessment (LCA), environmental life cycle performance, architectural design, design space exploration

1 INTRODUCTION

Life Cycle Assessment (LCA) is becoming more and more important for building evaluation in the scientific context [1] and in architectural practice – mostly in the form of building certification labels, e.g. DGNB [2] and BNB [3]. In those cases the LCA is used at a late stage of the design to evaluate the environmental impact and fulfil the requirements of the certification label. However, only evaluating the building design through LCA is not sufficient on its own if the results are not used to improve the design [4].

In order to minimize environmental impacts, an optimization is needed. In general, optimization of the design can best be achieved in early design stages, because decisions made in those stages have the biggest influence on energy demand [5] and environmental impact [6] while showing the smallest costs for changes to the design [7].

Usually, the architectural design process begins with geometric variants for the building shape and finally defining the geometry of the building. However, the most fundamental decisions, considering the geometry of the building, e.g. shape, orientation, window layout, are made with little or no involvement of simulation software [8]. A measure for the environmental performance of the building during the whole life cycle, which in the following is referred to as life cycle performance (LCP), would be valuable to provide a basis for deciding between geometric variants.

When conducting LCA in early design stages numerous challenges arise. In this paper, we address three main challenges:

(i) In contrast to well-defined problems with an apparent goal and end, architectural design problems are ill-defined where both the end and the means for a solution are unknown [9]. Subsequently,

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many alternative solutions exist and design becomes a process of selecting amongst them.

(ii) The numerous design parameters, such as geometry, materials and HVAC systems influence each other, making a separate optimization impractical.

(iii) Information necessary for LCA including specific data on the building materials and HVAC systems is usually not available in conceptual design stages. Once this information is available in later design stages, changes based on LCA results are hard to implement, because they would induce high costs and effort.

To address these challenges, we propose to combine a method for multi-stage design space exploration [10] with a parametric LCA method described in [11], [12], which can easily generate variants as basis for optimization. The proposed approach is exemplified using a case study of a residential building. The aim is to evaluate the potential life cycle performance (PLCP) of different geometric variants in the conceptual design stage in order to help the designer decide which geometry to choose for further planning stages.

2 METHODS

The design process is regarded as a search process, whereby variants are generated, evaluated, selected and improved in an iterative manner [13]. Rittel [10] describes several ways to search for solutions (explore the solution space). These range from a linear approach, where no alternatives are created (Fig. *1*a); to a single stage variant-selection approach, where for each aspect of a design variants are created, the best is chosen, and from there other aspects are considered (Fig. *1*b); to a multi-stage approach, where for each aspect all variants are considered (Fig. *1*c).

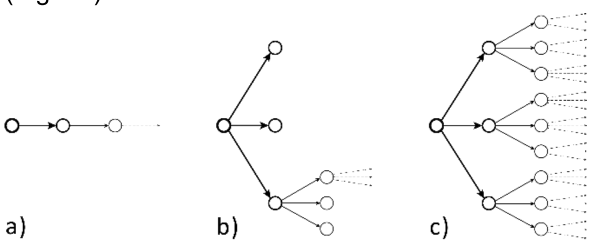

Fig. 1: Linear process (a), single-stage variant selection (b) and multi-stage variant selection (c), based on [10].

This last strategy can, for example, consist of the following steps: first, three variants for the shape of the building are created; second, three floor plans are created for each of them; third, several window layouts are created for each of the floor plans; fourth, building materials are chosen for each of these variants and finally HVAC systems are selected (of course the order in which these aspects are processed may vary).

This strategy is the most beneficial in order to not miss out potentially good solutions. However, this is also the most time-consuming one, due to the immense number of combinations that are possible. Thus, parts of this process need to be automated, because a designer is not able to manually create and evaluate all variants.

We assume that variants of the building geometry are created in the very early branching phases of the decision tree shown in Figure 1c. The method aims for estimating the PLCP that a building geometry offers, regardless of additional information on materials or HVAC systems. Therefore, the process of creating variants for materials and HVAC is simulated. The LCP is calculated for all resulting possible combinations. The range of LCP a building geometry achieves is used to characterise the PLCP.

To quickly calculate the LCP, a previously developed LCA method is used [11]. This method divides all necessary input into three categories, namely geometric information, non-geometric information and surrounding conditions. All input in those categories is defined parametrically, permitting quick adaption and variation. To facilitate the input of the geometry, a simple 3D CAD model consisting only of surfaces is employed. The surface areas are extracted automatically. The thicknesses of building components, material properties and other non-geometric parameters are defined numerically. Surrounding conditions, such as climate or user data, are taken from standards.

To carry out a building LCA, three kinds of material data are necessary: environmental data, reference service life (RSL) data and physical properties. Environmental data based on ökobau.dat version 2011 [14] and typical values for the RSL are chosen according to [15] and DGNB [2]. Physical properties such as thermal conductivity are taken from DIN 4108-4 [16].

A catalogue of the most common building components is established to reduce the effort of data input. The level of detail corresponds to the simplified input of materials as recommended by DGNB [2]. All components which are part of the thermal building envelope (exterior wall, roof, slab/basement ceiling) are defined using two layers. Layer A consists of all materials with predefined thicknesses except the insulation material. Layer B consists of the insulation material with a variable thickness in order to adapt the u-value of the component. Other building components are defined only using one fixed layer A.

It is distinguished between operational impact (I_O), which consists of life cycle module B6 according to EN 15987 [17] and embodied impact (I_E) which consists of modules A1-A3, B4, C3,

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C4, and D. Both are calculated separately and then added together to provide the life cycle impact (I_{LC}), see Eq.1. The operational impact consists of the sum of all different kinds of energy demand during the use phase (ED_i) divided by a performance factor (PF_i) for the specific building services, multiplied by the impact factor of the energy carrier ($IF_{O,i}$), and multiplied by the number of years of the reference service period (RSP), see Eq.2. The embodied impact of one material is calculated by multiplying the mass (M_j) by the specific impact factor of the material ($IF_{E,j}$) and by the number of replacements (R_j), see Eq.3. In this way, the embodied impact of every component is calculated and summed up to the embodied impact of the complete building.

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

$$I_O = \sum_i (ED_i \,/\, PF_i \times IF_{O,i}) \times RSP \quad (2)$$

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

To apply this parametric LCA method it has been implemented in a parametric design software called Grasshopper3D (GH) [18]. Both, the calculation of energy demand and embodied impact are fully integrated into GH, making exporting and re-importing unnecessary. We implemented DIN V 18599-2:2011 [19] in GH for the energy demand calculation and the implementation has been verified for residential buildings [20]. The developed parametric LCA tool is able to provide results in real time (< 0.1 s).

The results are reported for the indicators defined in EN 15987 [17]. According to ISO 14040 [21] weighting steps are based on value-choices and not scientifically based. Kägi et al. [22] report that decision makers always have to aggregate the LCA results in order make a decision on it. They furthermore discuss that it might be better to provide a single score for decision makers instead of letting them make the weighting on their own. The parametric LCA tool allows the advanced user to define and adapt own weighting factors in order to consider individual goals of the LCA study. Furthermore, it allows to employ different predefined weighting factors, e.g. those of building certification systems. For the calculation of LCP in this paper, we implemented the calculation of evaluation points (Bewertungspunkte, BP) of DGNB for both criteria related to LCA, namely ENV 1.1 and 2.1. These are weighted according to the DGNB system for residential buildings and combined into one value, which is called weighted BP (WBP) here.

To provide an example of application we present a case study of the design optimization of a new residential building in the following. The aim is to find the PLCP of six different geometric building typologies. Furthermore, it is investigated to which degree the geometry determines the LCP.

3 CASE STUDY

The building to be designed should provide eight apartments with a gross floor area (GFA) of 150 m² each. Six geometric variants are compared, each representing one typical type of residential building. To cover a wide span of geometries the variants range from detached houses to an apartment tower. For each geometric variant we assume six different kinds of heating systems and six combinations of typical building materials. Furthermore, three different u-values of the thermal building envelope representing different levels of energy standards are used to generate material variants. This results in 108 possible variants for each of the six building types.

The geometry for each building type is modelled in Rhinoceros [23], while all other necessary data is input in GH. Screenshots of the types and the variants for heating systems (H), building materials (M), and u-values (U) are provided in Table 1. Furthermore, we made the following assumptions:

- The functional unit is the usage of 1 m² net floor area (NFA) for 1 year.
- The NFA equals 0.8 × GFA.
- The RSP is 50 years.
- The buildings are located in a suburban context without shading from neighbouring buildings in Potsdam, Germany.
- The storey height is 3 m.
- The buildings do not have basements.
- The window area is 1/8 of the NFA of each storey, which is in line with the minimum requirement according to German state building regulations [24].
- The ventilation occurs naturally.
- The electricity demand is 20 kWh/m²a.

4 RESULTS AND DISCUSSION

All 648 possible variants have been calculated in a loop, which took less than 70 seconds showing the time-efficiency of the parametric LCA tool. The WBP that each of the six typologies achieved have been exported to Excel. To display the results, the WBP have been normalized to the maximum which can be achieved. To visualize the range of results, we use a boxplot, see Figure 2.

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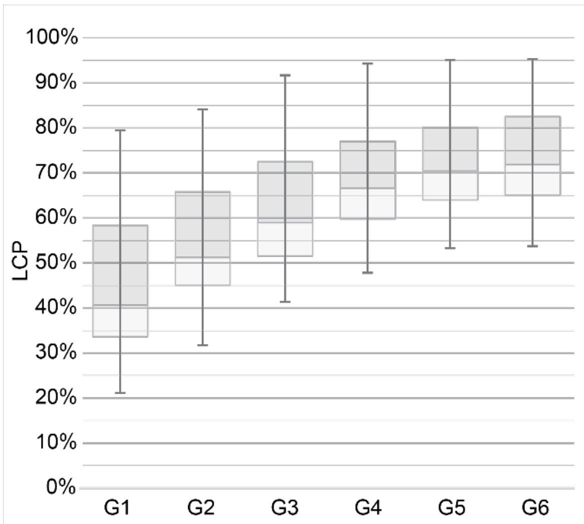

Fig. 2: Boxplot showing the range of LCP for each building geometry.

The boxplot indicates three main aspects: First, the ends of the vertical line (whisker) indicate the maximum and minimum LCP that can be achieved by a geometric variant. Second, the horizontal line within the box marks the median of all analysed solutions. As such, it indicates the LCP that is reached with a probability of 50%. Finally, the ends of the box indicate the first and third quartile which means that 50% of the possible solutions possess an LCP within the range of the box. The length of the whisker and the size of the box show to which degree the geometry determines the LCP that can be achieved. The designer can use this information for deciding which geometric variant should be pursued in the following detailed design stages.

The results can also be used to show to which degree the other parameters (H, M, and U) determine the LCP. To analyse the influence of one category on the PLCP, parameters from other categories have been fixed.

Figure 3 shows the PLCP for three heating systems (H6, H4, and H1) in dependence of the geometric variants. The heating systems represent the environmentally best (H6) and worst solution (H1) and an average solution (H4). The combination of building materials and the u-value have been fixed (M1 and U2). The results indicate that a relatively large range of LCP can be achieved through variation of the heating system. However, the best heating system (H6) only reaches the third quartile of all possible solutions. Even for the best geometric variant (G6) only about 80% of the maximum LCP can be achieved.

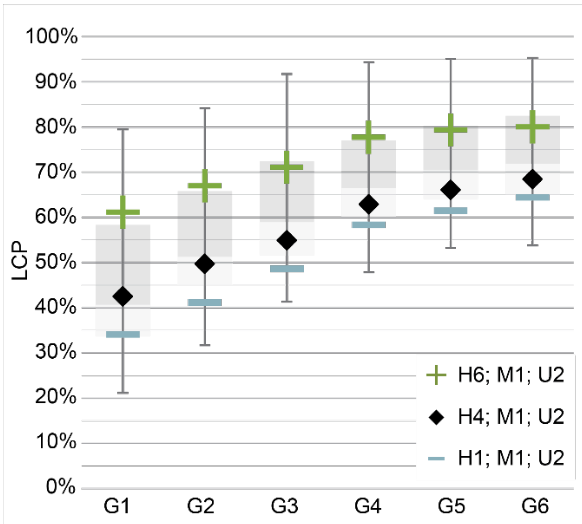

Fig. 3: LCP for three heating systems with fixed material and u-value.

The influence of the choice of building materials on the PLCP can be investigated likewise. Figure 4 shows the results for three combinations of materials (M1, M4 and M5) with a fixed heating system of average performance (H4) and a high-level u-value (U2). M1 lies close to the median for all geometric variants. The environmentally worst material variant (M5) lies just under M1. The environmental advantages of wooden constructions are reflected by the LCP of M4 which reaches between 79.5 and 94.5% of the maximum LCP in combination with H4 and U2.

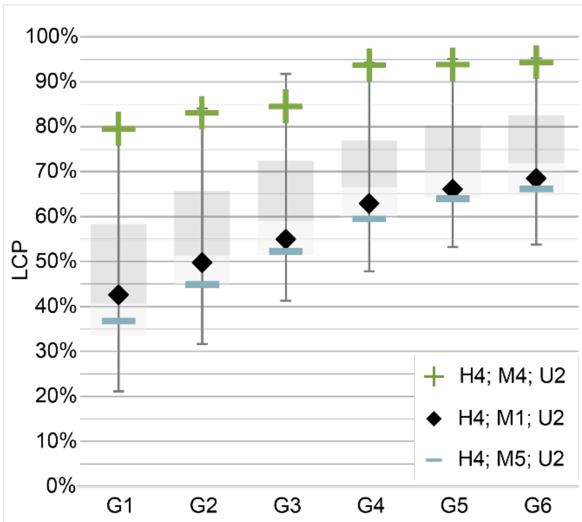

Fig. 4: LCP for three combinations of building materials with fixed heating system and u-value.

5 CONCLUSIONS

When aiming for a high LCP during the design of a building, ideally a multi-stage design space exploration would be carried out. However, this is difficult in practice, due to the high effort this approach involves and the missing information in early design stages. Therefore, we proposed a method that calculates a range of plausible solutions in each step based on assumptions for

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HVAC systems, building materials, and energy standards of the building envelope. The results provided a forecast of the LCP that can potentially be achieved later. As such, the method can be used to identify building geometries with a high PLCP. This helps the designer to choose a geometry for further planning stages.

Ideally speaking, this method frees the designer from worrying about HVAC systems and building materials in early design stages and allows to focus on the geometry. The PLCP approach integrates information of HVAC systems and building materials in the geometry. Using this measure the designer can optimize the geometry without having information usually required for an LCA. As such it provides a solution to the challenges mentioned in the introduction.

6 ACKNOWLEDGMENTS

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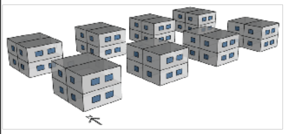
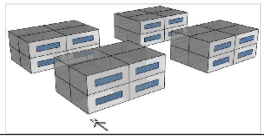
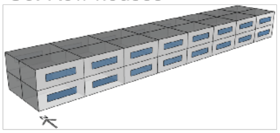
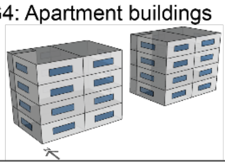
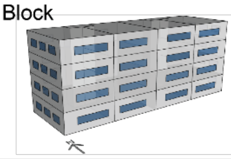
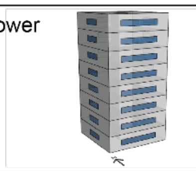
Geometry	Heating system	Building materials	U-value
G1: Detached houses 	H1: Gas fuelled heat pump (air) + floor heating	M1: ETICS Ext. walls: lime sand stone, EPS, plaster Roof: gravel, reinforced concrete, XPS Ceilings: floor tiles, reinforced concrete Int. walls: lime sand stone, plaster	U1: EnEV 2002 Ext. walls: 0.45 W/(m²K) Roof: 0.30 W/(m²K) Slab: 0.50 W/(m²K) Win.: 1.30 W/(m²K)
G2: Semi-detached houses 	H2: Electricity fuelled heat pump (earth) + floor heating	M2: Brick Ext. walls: insulating brick, plaster Roof: gravel, reinforced concrete, XPS Ceilings: floor tiles, reinforced concrete Int. walls: brick, plaster	U2: EnEV 2014 Ext. walls: 0.28 W/(m²K) Roof: 0.20 W/(m²K) Slab: 0.35 W/(m²K) Win.: 1.30 W/(m²K)
G3: Row houses 	H3: Gas-condensing boiler + floor heating	M3: Concrete Ext. walls: reinforced concrete, EPS Roof: gravel, reinforced concrete, XPS Ceilings: floor tiles, reinforced concrete Int. walls: reinforced concrete	U3: Passivhaus Ext. walls: 0.15 W/(m²K) Roof: 0.15 W/(m²K) Slab: 0.15 W/(m²K) Win.: 0.80 W/(m²K)
G4: Apartment buildings 	H4: Gas-condensing boiler + radiators	M4: Wood Ext. walls: wood cladding, timber frame, WFIB, OSB Roof: bitumen, timber beams, WFIB Ceilings: wood floor, timber beams Int. walls: wood cladding, timber frame	
G5: Block 	H5: Woodchip boiler + floor heating	M5: Ventilated facade Ext. walls: wood cladding, air layer, rockwool, lime sand stone, plaster Roof: gravel, reinforced concrete, XPS Ceilings: floor tiles, reinforced concrete Int. walls: lime sand stone, plaster	
G6: Tower 	H6: District heating + floor heating	M6: Double shell masonry Ext. walls: clinker brick, CIB, brick, plaster Roof: bitumen, timber beams, WFIB Ceilings: floor tiles, reinforced concrete Int. walls: wood cladding, timber frame	

Abbreviations:
EPS: Expanded polystyrene
XPS: Extruded polystyrene
PUR: Polyurethane
WFIB: Wood fibre insulation board
CIB: Cellulose insulation board

For all variants:
Slab: reinforced concrete, PUR;
Windows: PVC frame, double pane for EnEV 2002 and EnEV 2014, triple pane for Passivhaus
All components possess a fire resistance F60

Table 1: Overview of variants.

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