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Abstract Life Cycle Assessment (LCA) is increasingly used for buildings, however, mostly for post-design evaluation of the environmental impact. To use the results for optimization, LCA has to be integrated in the early design stages. While Building Information Modelling (BIM) is more and more applied in detailed design stages, simple 3D models are typically used to compare design variants in early stages. The objective of this paper is to introduce a simplified, design-integrated method based on these early BIM models with limited information. The early BIM-LCA method uses simple 3D geometry and a parametric LCA model. Methodological simplifications are introduced and a single indicator based on the DGNB certification system is used to provide an intuitive real-time feedback for the designer. The method is applied to the conceptional design of a residential neighbourhood. The results highlight the great potential of using simplified LCA to quantify environmental performance for decision-making in early design stages.

1   Introduction

Life Cycle Assessment (LCA) is increasingly gaining importance for environmental evaluation of buildings, mostly in the form of building certification labels. The application of LCA at a late stage of the planning process for post-design evaluation of the environmental impact is not sufficient on its own if the results are not used to improve the design [1]. The highest optimization potential lies within the early design stages where the decisions made have the biggest influence on energy demand [2] and environmental impact [3] while featuring the smallest costs for changes to the design [4]. Optimization in these early design stages can only be achieved by generating and comparing design variants. To allow for design-integrated assessment of the environmental performance a simplified and time-efficient method for LCA is needed. The additional effort for designers has to be kept to a minimum to avoid barriers for assessment. Therefore, tools for LCA should

ideally be integrated in the usual design environment. Recently, various solutions to integrated LCA using BIM have been developed [5]. However, the conventional BIM is typically used in detailed design stages [6]. In early design stages, conceptional mass models are employed to quickly modify and generate variants at a low level of detail. Therefore, this paper discusses the use of simplified digital building models – referred to as early BIM – for LCA. The objective is allow for time-efficient improvement of the environmental performance in early design at a point where many parameters needed for conventional BIM-LCA approaches are still unknown. The proposed approach is applied to a case study of the conceptional design of a neighborhood.

2   Early BIM-LCA using parametric models

The early BIM-LCA approach uses simplified digital building representations. These 3D models only consist of surfaces instead of volumetric components, see Fig. 1. This approach is also referred to as "shoebox" models [7] and is commonly employed in thermal models for energy demand calculation. The input of interior walls can be further simplified by using a global factor instead of modelling each individual wall, provided in Minergie guidelines [8], for example.

Fig. 1:   Simplified building representation using surfaces only
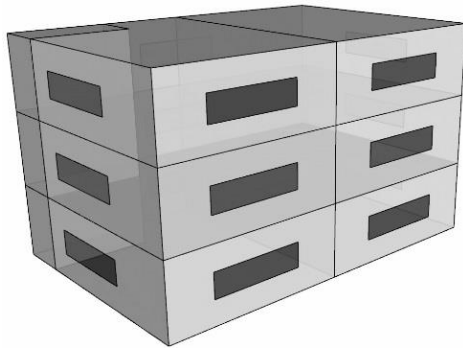
For a simplified input of materials, a building component catalogue of typically employed materials and HVAC systems can be used. A variety of typical building components including LCA data can be found in many national catalogues, such as *Bauteilkatalog* [9] for Switzerland, *Milieuprofiel van gebouwelementen* [10] for Belgium, or *Baubook* [11] for Austria.

The calculation of the LCA is carried out using a parametric model [12]. The designer can typically influence three categories of parameters of a building: geometry, materials and HVAC systems [12]. Each category consists of a number of parameters, such as orientation, dimensions, window area, etc. for the geometry. The parametric LCA approach combines the calculation of the operational and embodied environmental impact. The operational impact results from the use phase of the building (life cycle module B6 according to EN 15978 [13]) and is based on an energy demand calculation using monthly energy balancing [14]. The embodied impact results from the material production, replacements and the end-of-life (life cycle modules A1-A3, B4, C3, C4, and D). The implementation of the parametric LCA in a design tool such as Grasshopper [15] allows for a closed workflow of input, calculation, output without requiring any importing/exporting [16]. This is necessary for comparing variants automatically and the basis for computational optimization approaches.

The parametric approach allows an advanced user to define and adjust their own weighting factors in order to consider the individual goals of the LCA study [16]. Furthermore, it allows for employing different predefined weighting factors, such as those from building certification systems. DGNB employs two criteria based on LCA and awards points for each [17]. These are weighted and combined into one indicator called life cycle performance (LCP) [18]. This single indicator ranges from 0-1, with 1 being equal to 100% of the DGNB points related LCA criteria.

3　Case study

In the following case study, the method is applied to the early design stages of a hypothetical residential neighbourhood providing a total gross floor area (GFA) of 2500 m². Between two and four buildings are located on a rectangular site in Potsdam, Germany. The storey height of all apartments is 3 m, and the buildings do not have basements. The floor area ratio (FAR) is set to 0.6 and minimum and maximum dimensions are set to ensure reasonable sizing of the building volumes. The buildings can have two to four floors and the glazing area is constantly 30 % of the exterior wall area. It is assumed that the net floor area (NFA) equals $0.8 \times$ GFA. The functional unit is 1 m² NFA for 1 year, and the reference study period is 50 years. Both climate and user data are taken from DIN V 18599-10:2011 [19].

It is assumed that the design process occurs in two stages, first definition of geometry, second choice of materials. The HVAC systems are not modified

parametrically but fixed. The heating system is set to a gas-condensing boiler with an efficiency of 98%, no cooling is considered and the ventilation occurs naturally.

For the first stage of defining the gemeotry, a generating algorithm positions buildings on the site. Due to the parametric positioning, it is likely that the buildings intersect initially. The algorithm resolves the intersections and maintains a pre-set minimum distance between the buildings [20]. A solar analysis is integrated to account for shading of the different buildings. Additionally, cores including the main circulation spaces within the buildings are inserted. In order to enable natural lighting and ventilation, they are only positioned at exterior walls, preferably in shaded areas to keep the solar gains to the usable floor spaces. If a building exceeds a defined building size, further circulation cores are added. The interior walls are not included in the 3D model, but instead input numerically based on a overall average factor of 0.4 m²GFA following the Swiss Minergie regulation [8]. All of those model features are parametrically controlled and each combination of the parameter values generates different design variants. The algorithm can quickly generate thousands of possible variants, which can be used for optimization [21]. The focus of the case study is the application of the early BIM-LCA method. Therefore, nine variants showing different geometric characteristics, such as number and position of buildings are chosen for stage 2.

In the second stage, the resulting building volumes are combined with six different construction types. For each construction type four building components – exterior walls, interior walls, ceilings, roofs – are manually generated, see Tab.1. The individual materials of the constructions can be found in Tab.2. The windows and the slab are the same for each construction type. The slab is made of reinforced concrete and polyurethane insulation; the windows consist of a PVC frame with double glazing. The U-values for the building components of different construction types are the same and follow the minimum U-value of the 2014 German Energy Efficiency Regulation (EnEV) [22]. As such, the operational energy demand is only influenced by the geometry and not the thermal quality of the building envelope. Furthermore, all components possess a fire resistance of at least 60 minutes. LCA data for the materials are taken from the German *oekobau.dat* database [23]. Using a calculation loop [18], the LCP values for each variant are calculated.

Tab.1: **Different construction types**

Construction type	Exterior wall	Roof	Ceiling	Interior wall
ETICS	ETICS	Concrete	Concrete	Lime-sand stone
Brick	Insulated brick	Concrete	Concrete	Brick
Concrete	Concrete	Concrete	Concrete	Concrete
Wood	Wood frame	Wood beams	Wood beams	Wood frame
Ventilated facade	Ventilated facade	Concrete	Concrete	Lime-sand stone
Double shell masonry	Double shell masonry	Wood beams	Concrete	Wood frame

4   Results

Combining nine geometric variants with six construction types results in 54 solutions. The results are visualized in a tree with two stages, see Fig. 2. The LCP show a high range of 0.376 between the minimum value of 0.580 (variant 7, concrete) and the maximum value 0.956 (variant 3, wood). The median of the six different construction types is calculated to evaluate the geometry independent of the choice of material. Variant 3 performs best according to the median LCP. Variant 3 also achieves the maximum overall performance in stage 2, when the wood-based construction variant is chosen. Variant 7 achieves least LCP according to the median and performs worst in both cases, when choosing wood or concrete.
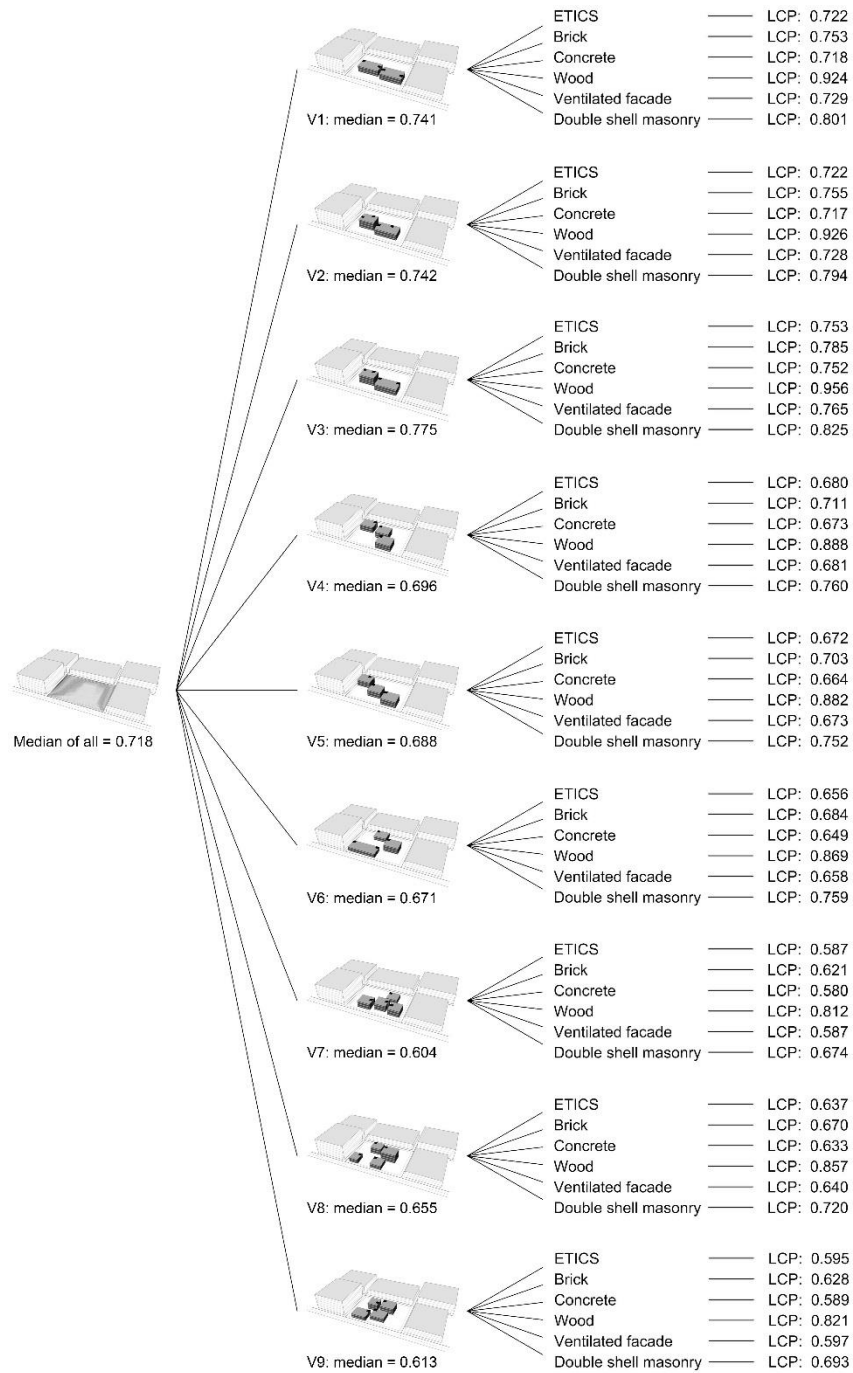
ETICS ————— LCP: 0.722
Brick ————— LCP: 0.753
Concrete ————— LCP: 0.718
Wood ————— LCP: 0.924
Ventilated facade ————— LCP: 0.729
Double shell masonry ——— LCP: 0.801

V1: median = 0.741

ETICS ————— LCP: 0.722
Brick ————— LCP: 0.755
Concrete ————— LCP: 0.717
Wood ————— LCP: 0.926
Ventilated facade ————— LCP: 0.728
Double shell masonry ——— LCP: 0.794

V2: median = 0.742

ETICS ————— LCP: 0.753
Brick ————— LCP: 0.785
Concrete ————— LCP: 0.752
Wood ————— LCP: 0.956
Ventilated facade ————— LCP: 0.765
Double shell masonry ——— LCP: 0.825

V3: median = 0.775

ETICS ————— LCP: 0.680
Brick ————— LCP: 0.711
Concrete ————— LCP: 0.673
Wood ————— LCP: 0.888
Ventilated facade ————— LCP: 0.681
Double shell masonry ——— LCP: 0.760

V4: median = 0.696

ETICS ————— LCP: 0.672
Brick ————— LCP: 0.703
Concrete ————— LCP: 0.664
Wood ————— LCP: 0.882
Ventilated facade ————— LCP: 0.673
Double shell masonry ——— LCP: 0.752

V5: median = 0.688

Median of all = 0.718

ETICS ————— LCP: 0.656
Brick ————— LCP: 0.684
Concrete ————— LCP: 0.649
Wood ————— LCP: 0.869
Ventilated facade ————— LCP: 0.658
Double shell masonry ——— LCP: 0.759

V6: median = 0.671

ETICS ————— LCP: 0.587
Brick ————— LCP: 0.621
Concrete ————— LCP: 0.580
Wood ————— LCP: 0.812
Ventilated facade ————— LCP: 0.587
Double shell masonry ——— LCP: 0.674

V7: median = 0.604

ETICS ————— LCP: 0.637
Brick ————— LCP: 0.670
Concrete ————— LCP: 0.633
Wood ————— LCP: 0.857
Ventilated facade ————— LCP: 0.640
Double shell masonry ——— LCP: 0.720

V8: median = 0.655

ETICS ————— LCP: 0.595
Brick ————— LCP: 0.628
Concrete ————— LCP: 0.589
Wood ————— LCP: 0.821
Ventilated facade ————— LCP: 0.597
Double shell masonry ——— LCP: 0.693

V9: median = 0.613

Fig. 2: LCP results for design tree

The difference between the median of worst and best geometric variant is 0.17 showing that the influence of the geometry is significant. With a range of 0.22 LCP, the average range of the different material combinations is even higher. This clearly shows the great importance of the choice of material. The best solutions can be achieved with the wooden construction for all geometries in this case study. Even the worst geometric variant with wooden construction performs better than the best geometric variant built in ETICS, brick, concrete or a ventilated façade, see Fig. 3.
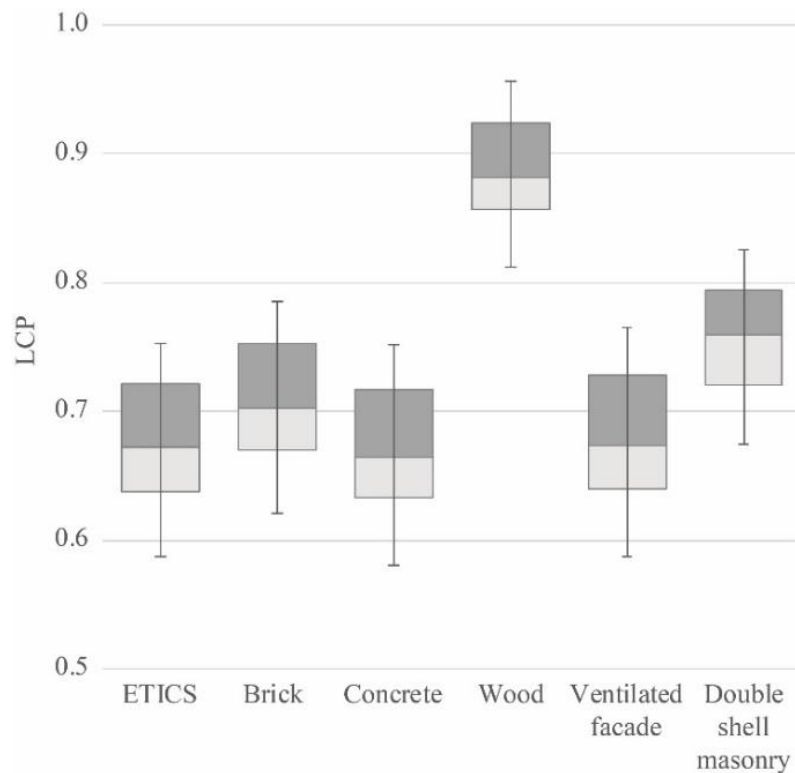

Fig. 3: **Ranges of material choice**

5 Discussion

The results highlight the importance of materials choices. In this case study, the median proves to be a robust indicator of the environmental performance in stage 2. It can be used to evaluate and rank design solutions in stage 1 without having defined the exact material. This is important for application in practice, because

usually there is no time for elaborate studies, such as presented here. A simple measure to indicate the environmentally best performing variants to the design team is needed. By automatically looping through a number of material variants and calculating the median this simple measure can be provided easily and time-efficiently. In the case study, each calculation took less than 0.1 seconds, which allows to calculate the median within less than 0.6 seconds. According to Nielsen [24] a response time of 1 second is acceptable for designers to not feel interrupted in their flow of thoughts. As such, the computer can loop through typical materials and provide an LCP before materials have been assigned. Using this measure the designer can optimize the geometry without having information usually required for an LCA. Ideally speaking, this method frees the designer from worrying about HVAC systems and building materials in early design stages and allows focusing on the geometry.

6   Conclusion & outlook

Design-integrated, simplified LCA based on digital building models can help to make informed environmental decisions during conceptional design. The early BIM-LCA approach using a parametric model presented here, proves to be valuable for quick variant comparison of neighbourhoods in early design stages. The simplified visualization and the use of a single indicator can help designers to make informed decisions based on the LCA results. These simplified approaches are necessary to move from the current post-design evaluation of buildings to a design-integrated assessment. This finally allows designers to improve the environmental performance of their buildings from the very beginning of the planning process.

Through the development towards *nearly zero energy buildings*, buildings produce more and more of the energy they need for operation themselves. As such, the integration of local energy production should be integrated in the assessment. This aspect could be easily integrated in the parametric LCA model. Furthermore, the link to further analysis methods, such as daylight availability could provide a means to extend the early BIM-LCA to a more holistic performance evaluation tool in the future.

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Tab.2: **Materials of the different building elements**

	Construction type	Material	cm
Exterior walls	External thermal insulation composite systems (ETICS)	Synthetic plaster	0.20
		Fibre glas reinforcement grid	0.05
		Synthetic resin	0.04
		EPS	13.00
		Synthetic resin	0.04
		Lime-sand stone	24.00
		Gypsum plaster	1.50
	Brick	Plaster	2.00
		Insulated brick	26.00
		Plaster	2.00
	Concrete	Plaster	0.20
		Fibre glas reinforcement grid	0.05
		Synthetic resin	0.04
		EPS	13.00
		Synthetic resin	0.20
		Concrete C20/25	15.00
		Reinforcement	0.3* (2 Vol%)
	Ventilated facade	Wood cladding	2.40
		Wood laths 40/60 mm	0.048*
		Sheathing membrane	0.08
		Rock wool	11.00
		Lime sand stone	24.00
		Plaster	1.50
	Wood frame	Wood cladding	0.20
		Wood laths 40/60 mm	0.048*
		Wood fibre board	3.00
		Gypsum plaster board	0.95
		Wood beam 12/18 cm	2.16*
		Wood fibre insulation board	11.00
		OSB board	1.80
		Gypsum plaster board	1.50
	Double shell masonry	Facing brick	12.50
		Cellulose insulation boards	6.00
		Brick	24.00
		Gypsum plaster	1.50
Roofs	Concrete	Gravel 2/32	4.00
		Bitumen sheeting	0.80
		XPS	18.00
		Vapor barrier PA	0.30
		Concrete C20/25	20.00
		Reinforcement	0.8* (4 Vol%)
		Gypsum plaster	1.50
	Wood beams	Bitumen sheeting	0.80
		Wood fibre insulation board	18.00
		Vapor barrier PA	0.30
		Wood planking	2.40
		Wood beam 12/18 cm	2.16*

Ceilings	Concrete	Tiles	1.00
		Tile adhesive	0.80
		Cement screed	6.00
		Vapor barrier PE	0.02
		Concrete C20/25	18.00
		Reinforcement	0.72* (4 Vol%)
		Gypsum plaster	1.50
	Wood beams	Parquet floor	2.00
		Dry screed	2.50
		Wood fibre footstep sound insulation	2.00
		Chipboard	2.50
		Wood beam 12/18 cm	2.16
		Vapor barrier PE	0.02
		Wood laths 30/60 mm	0.036*
		Wood cladding	2.40
Interior walls	Concrete	Gypsum plaster	1.50
		Concrete C20/25	10.00
		Reinforcement (2 %)	0.20*
		Gypsum plaster	1.50
	Lime-sand stone	Gypsum plaster	1.50
		Lime sand stone	11.50
		Gypsum plaster	1.50
	Brick	Gypsum plaster	1.50
		Brick	11.50
		Gypsum plaster	1.50
	Wood frame	OSB board	1.80
		Wood beam 6/8cm	3.00*
		Rock wool	7.50
		OSB board	0.90
Slabs	Concrete	Tiles	1.00
		Tile adhesive	0.80
		Cement screed	6.00
		Vapor barrier PE	0.02
		XPS	10.00
		Bitumen sheeting	0.40
		Concrete C20/25	25.00
		Reinforcement	1.00* (4 Vol%)
		Lean concrete	8.00