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Using a budget approach for decision-support in the design process

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Abstract. The use of Life Cycle Assessment (LCA) during the design phase can help to improve the environmental performance of buildings. However, designers and clients find it difficult to set environmental performance targets and interpret the results obtained through LCA in order to improve the building design. Therefore, performance levels or benchmarks are needed that provide design guidance towards reducing the environmental impacts of buildings in the life cycle. This paper uses a dual benchmark approach. The main concept consists in combining building-related top-down targets with building component-related bottom-up benchmarks. The overall top-down targets per capita and year are derived from the capacity of the global eco system. The bottom-up benchmarks for building elements are calculated following a best-in-class (top 5%) approach. A workflow of applying these benchmarks is proposed. It provides guidance on how to optimize the environmental performance of a building and its components efficiently by differentiating between material and design-related options. The approach is exemplified by means of a case study of a multi-family house.

1. Introduction

Until now, the efforts to reduce greenhouse gas (GHG) emissions in the building sector mainly focused on the use phase of buildings. Due to the achievements in reducing the operational energy demand, amongst other reasons, researchers have turned to other fields to investigate additional saving potentials. An important aspect are the so-called embodied GHG emissions related to the manufacturing of construction products and to the construction, maintenance and end of life of buildings. Early design decisions largely determine the environmental performance of the building [1] for the next 50 to 100 years. Therefore, designers are key actors for reducing global GHG emissions during the life cycle of individual buildings. Life Cycle Assessment (LCA) is a suitable method for evaluating the building's environmental performance, however, currently, designers often find it difficult to interpret the LCA results and use them to improve the building design. The importance of environmental benchmarks has been recognized early [2]. There is a demand for benchmarks on GHG emissions in the different phases of the building's life cycle that serve as an orientation for designers [3]. Therefore, benchmarks should provide design guidance from the beginning of the design. A number of software to facilitate LCA for designers has been published in the last years, e.g. Tally [4], oneClickLCA [5], Athena [6], or CAALA [7]. However, they do not provide benchmarks that indicate the potential for improvement during the design.

The goal of this paper is to propose the application of LCA-based benchmarks in the design process to support the reduction of the environmental impact of buildings - mainly through the choice of construction type and materials.

2. Method

This paper uses a *dual benchmark approach,* developed by the authors and described in detail in [8]. The main concept consists in combining top-down targets with bottom-up benchmarks. The top-down targets per capita and year are derived from the capacity of the global eco system. The bottom-up benchmarks for building elements are calculated following a best-in-class (top 5%) approach. In this paper, the overall target of 1 t CO_2-e per capita and year by the year 2050 is used to define a top-down target. According to the Swiss 2000 Watt society [9], but also according to the German Environment Agency [10], this value is sufficient to achieve “climate neutrality”. The target values as defined in SIA 2040 [11] are employed, however, they are adapted to meet the global target of 1 t CO_2-e/(c·a). To describe the potential impact on climate change the indicator Global Warming Potential 100 (GWP) expressed in kg CO_2-equivalent as defined by IPCC [12] is used. The target values per capita and year for the domain of housing in Switzerland are shown in Table 1.

Table 1. Target values for GWP per capita and year for the domain of housing in Switzerland based on SIA2040 and adapted to the global target of 1 t CO_2-e per capita and year

	GWP [kg CO_2-e/(c·a)]
Embodied (including manufacturing, replacement and end of life)	270
Operation (building-related part)	90
Total	360

The bottom-up reference values for building elements are defined based on a statistical best-in-class approach (top 5%) using the market share of different construction products. The minimum, weighted mean and target values are shown in Table 2. The target values are based on 1 m^2 of surface area of the individual building element. Only the target values for columns are given per m length. Target values for technical equipment are provided per floor area of energy reference area (A_E), which corresponds to the gross floor area of the heated building zones.

Table 2. Minimum, weighted mean and target values (0.05 quantile) for GWP for the building elements for Swiss multi-family houses

Building element	**Sample size**	**Reference unit (unit)**	**GWP [kg CO_2-e/(unit·a)]**		
			Minimum	**W. mean**	**Target (0.05)**
1. Base slab	80	$m^2_{element}$	1.32	2.23	1.87
2. Exterior walls underground	3	$m^2_{element}$	3.52	3.72	3.35
3. Exterior walls aboveground	404	$m^2_{element}$	0.82	2.11	1.37
4. Windows	16	$m^2_{element}$	1.49	3.16	1.85
5. Interior walls	35	$m^2_{element}$	0.59	1.28	0.82
6. Partition walls	30	$m^2_{element}$	0.58	1.05	0.83
7. Columns	7	m	0.43	2.01	0.64
8. Ceilings	1260	$m^2_{element}$	0.66	2.24	1.37
9. Balconies	4	$m^2_{element}$	1.2	1.48	1.13
10. Roof	273	$m^2_{element}$	0.79	4.05	2.32
11. Technical equipment*	29	m^2_{AE}	1.18	-	1.18*

* Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used. The target value is the sum of minimum values for electric equipment, heat generation, heat distribution and delivery, ventilation equipment and water (sanitary) equipment of residential buildings.

The dual benchmark approach allows distinguishing between the different available options to reduce the embodied environmental impact of a building, namely the choice of type of construction/material and the design. Clearly, the choice of material is part of the design, however, in this context, both aspects are analysed separately. Design options refer to the shape and size of the building, but also the organization of floor plans or the window to wall ratio. Further aspects, such as the building's adaptability to react to changes in the use phase as well as building components' ability to be deconstructed and recycled are excluded here, but could be added in the future. Finally, the aim in the design phase should be reducing the environmental impact of the building holistically, including the operational part. There are many approaches for energy-efficient design described in the literature, see Energy Manual [13], for example. Here, the focus is therefore on the embodied part.

The proposed workflow of using the dual benchmark approach in the design process is visualized in Figure 1. EN 15643-1 [14] explicitly states that targets for the environmental performance shall be defined among others. Therefore, the workflow proposes to first calculate the environmental performance target based on the top-down benchmark. Then the environmental impact of the initial building design is calculated and compared to the top-down target. The impact of the individual building elements is calculated and compared to the bottom-up benchmarks to indicate the material-related optimization potential. If the selected "material/type of construction"-solution for an element is not within the top 5% of one or more assessment criteria – in this case the GWP, it is recommended to modify the material/type of construction and redo the analysis. There are exceptional cases where a specific material or type of construction cannot be changed due to other characteristics needed, e.g. fire or earthquake resistance. If the chosen solution is within the top 5% of a specific assessment criteria, the improvement potential is considered as small. In this case, it is assumed that the most efficient way to reduce the embodied impact is through design changes. For example, the compactness of the building can be increased, or the floor plans can be modified to decrease the built area. The change of the design has many consequences on other architectural and functional aspects, for example daylight availability and energy demand for lighting. These have to be considered, but are not within the scope of this paper. The aim of dividing between specific material/construction-type-related and overall design-related options is to provide guidance for environmental performance optimization of the building and its components. The proposed workflow is exemplified by means of a case study.

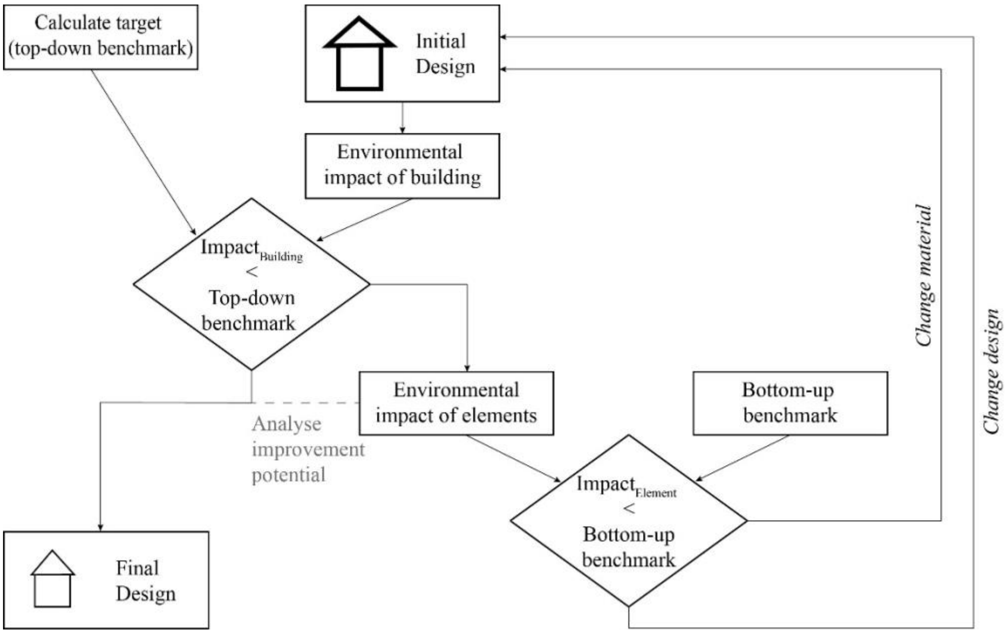

Figure 1. Flow chart of applying the dual benchmark approach in the design process

3. Case Study

To show the application of the benchmarks and validate the applicability of the proposed method, an existing building in Hamburg, Germany, called “Woodcube” is used as a case study. The reference study period is 60 years. The focus lies on analysing the embodied and the overall life cycle-related GWP and a comparison with the benchmarks. The operational GWP is calculated to provide the value in relation to the embodied part. Some small modifications to the geometry of the original building were made for simplification [15]. All material properties are taken from a published LCA report [16]. The quantities of the individual building components, respectively the areas of the building elements are taken off from a simplified 3D model, see Figure 2.

Figure 2. Left Woodcube (photo Hollberg), right simplified 3D model of the building

The assessment of the embodied impact for buildings in Switzerland is regulated in the standard SIA 2032 [17], which is currently revised and updated. The standard defines which building elements have to be included in the assessment. It refers to the elements defined in the Swiss standard for building cost regulation SN 506 500 [18] “Baukostenplan Hochbau” (BKP-H). In Switzerland, a building component catalogue [19] provides GWP factors for typical building components. It is based on the national Swiss database *KBOB Ökobilanzen im Baubereich* [20]. The building elements with the respective areas and related building components from the building component catalogue are listed in

Table 3. The GWP factors are provided including manufacturing (life cycle modules A1-A3 according to EN 15978 [21]) and end-of-life (modules C3 and C4). The values are provided per year taking the reference service life of the component declared in SIA 2032 [17] into account. When the values are multiplied with the reference study period of 60 years for residential buildings in Switzerland, the replacement (module B4) is implicitly considered.

Table 3. GWP factors per year and per m^2 of element area from the building component catalogue organized along Swiss BKP-H structure

Building element	**Area [m^2]**	**Component according to BKP-H**	**Code / ID**	**Component name according to catalogue**	**GWP [kg CO_2-e/(m^2·a)]**
1. Foundation	228.0	C1 Base slab, foundation	C1 003	Flat foundation 5 or 6 storeys, Steel content 90 kg/m3, 35 cm	1.679
		G2 Floor covering	-	none	0.000
2. Exterior walls under ground	183.0	C2.1A Exterior wall under ground	C2.1A 029	Reinforced concrete wall, 20cm, Steel content 90 kg/m3	1.318
		E1 Exterior wall finishing under ground	-	none	0.000
3. Exterior walls above ground	723.5	C2.1B Exterior wall above ground	C2.1B 058	Timber frame construction	0.782
		E2 Exterior wall finishing above ground	-	Integrated in C2.1B	0.000
		G3 Interior wall finishing	G3 126	Timber cladding, painted	0.073
4. Window	200.7	E3 Window	E3 072	Double glazing, 10% timber frame	1.486
5. Interior walls	391.4	C2.2 Interior wall	C2.2 082	Reinforced concrete wall, Steel content 105 kg/m3	1.559
		G3 Interior wall finishing	-	none	0.000
6. Partition walls	643.0	G1 Partition wall	G1 107	Timber frame construction with insulation	0.541
		G3 Interior wall finishing	G3 127	Gypsum panel	0.170
7. Columns	0.0	C3 Column	-	none	0.000
8. Ceilings	1140.0	C4.1 Ceiling	C4.1 011	Timber frame ceiling	0.472
		G2 Floor covering	G2.2 108a	Sound insulation, anhydrite screed	0.321
		G4 Interior finishing	-	none	0.000
9. Balconies	90.0	C4.3 Balcony	C4.1 011	Timber frame ceiling	0.472
10. Roof	228.0	C4.4 Roof	C4.1 011	Timber frame ceiling	0.472
		F1 Roof covering	F1 017a	Foil sealing, EPS insulation	1.887
		G4 Interior finishing	-	none	0.000
11. Technical equipment	1099.0*	D1 Electric equipment	34.001	Electric installation, low requirements	0.310
		D5.2 Heat generation	31.002	Heat generation, power 30 W/m^2	0.080
		D5.3 / D5.4 Heat distribution / delivery	31.024	Floor heating	0.290
		D7 Ventilation	32.003	Ventilation in kitchens and bathrooms	0.150
		D8 Sanitary equipment	33.003	Sanitary equipment	0.510

* The technical equipment is provided per floor area of energy reference area (A_E), which corresponds to the gross floor area of the heated building zones.

To define a GWP budget as the target value for the building, the top-down benchmarks in Table 1 are multiplied with the number of residents. In the design phase, an assumption for the number of residents is needed. The number of rooms in each apartment are analysed based on the architects' floor plans [16] and three scenarios are defined with the following assumptions: A) 24 residents; two persons for each master bedroom and one for each child and guest room; B) 18 residents; some master bedrooms are occupied by two, some by one person and not all guest rooms are continuously occupied; and C) 14 residents; one or two persons for each master bedroom depending on the size of the apartment and one person for each two child/guest rooms. In scenario B, the average living space of the residents is 45.8 m^2, which is close to the Swiss average value of 45.0 m² [22] and close to the German average of 46.5 m² in the years 2016 and 2017 [23]. Therefore, scenario B is assumed to be most realistic and employed for this paper. The influence of the floor area per resident on the top-down target is discussed later. The resulting benchmarks for the building are shown in Table 4.

Table 4. Top-down benchmarks for the case study building in GWP

	GWP [kg CO_2-e/a]
Embodied (including manufacturing, replacement and end of life)	4860
Operation (building-related part)	1620
Total	6480

4. LCA results of the case study building and discussion

Multiplying the areas of the eleven elements with the GWP factors for the components provides the results per building element shown in Table 5. The column *Actual value* shows the results for the selected materials as built. In addition, the other columns show the statistical values for minimum and target value based on the 0.05 quantile according to the bottom-up benchmark approach. These values are needed for the comparison later.

Table 5. Results for the embodied GWP of the building case study

Building element	**GWP [kg CO_2-e/a]**		
	Target (0.05)	**Minimum**	**Actual value**
1. Base slab	426	301	383
2. Exterior walls underground	613	644	241
3. Exterior walls aboveground	991	593	619
4. Windows	371	299	298
5. Interior wall	321	231	610
6. Partition walls	534	373	457
7. Columns	0	0	0
8. Ceilings	1562	752	857
9. Balconies	102	108	43
10. Roof	529	180	538
11. Technical equipment*	1297*	1297	1381
Total building	**6746**	**4779**	**5518**

* Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used.

The building has a final energy demand for heating and hot water supply of 39674 kWh/a and an electricity demand (including auxiliary energy, ventilation, lighting and equipment) of 20212 kWh/a. The heating is provided though a wood chip boiler and the electricity by photovoltaic (PV) modules on the roof. The electricity demand can be fully covered by the building integrated PV on annual average. The factors for GWP are taken from the Swiss database *KBOB Ökobilanzen im Baubereich* [20]. The factors for the electricity from PV are based on a simplified approach of averaging all emissions within the life cycle such as production and disposal of the cells, but also the inverter and other parts of the system into one annual value per kWh. Excess energy exported into the grid is not considered to simplify the calculation. The benefit of exporting energy to the grid is highly dependent on the short-term variation of the electricity mix but also the long-term development in the next years. To assess the excess energy correctly, a dynamic approach considering the dynamic GWP factors for the Swiss grid would be needed [24], [25]. As this is not the focus of the paper, the calculation is simplified. The results are provided in Table 6.

Table 6. Results for GWP caused by operation of the case study building

	Final energy		**Energy source**	**GWP**	**GWP**
	[kWh/a]	**[kWh/(m^2_{AE}·a)]**		**Factor**	**[kg CO_2-e/a]**
Heating	39674	36.1	Wood chip boiler	0.027	436
Electricity	20212	18.4	PV on flat roof	0.081	1637
Total					**2073**

The total life cycle GWP of 7591 kg CO_2-e/a is 14.6 % higher than the top down target value of 6480 kg CO_2-e/a. Comparing the embodied and operational part separately shows that both parts are higher than the top-down benchmarks. Reductions of 11.9% for the embodied part and reductions of 21.8 % for the operational part are needed to meet the top-down benchmarks. As both parts do not meet the target values there is no opportunity to compensate one aspect with the other. Further alternatives to improve the building and reduce the environmental impacts are needed to make it compliant with the 1 t CO_2-e per capita and year approach.

Strategies to reduce the operational GHG emissions can be divided into approaches that influence the embodied impact e.g. increasing the insulation thickness and approaches that do not, such as choosing an alternative energy carrier. Here, it is assumed that approaches without influence on the embodied impact are followed. These could also include considering benefits from generating electricity onsite that is exported to others. As mentioned above, this raises further questions for example regarding system boundaries and allocation that cannot be discussed in detail is this paper. Furthermore, there are approaches that are beneficial for both operational and embodied impacts for example following a sufficiency strategy. This aspect is discussed later.

In the following, the case study focusses on the embodied impacts. To analyse how the embodied GHG emissions can be reduced best, the results for the building elements are compared to the bottom-up benchmarks. The results for the specific solutions are shown in the graph of the variability of the elements, see Figure 3, to indicate the improvement potential of each element. The points indicate the values for the specific solutions.

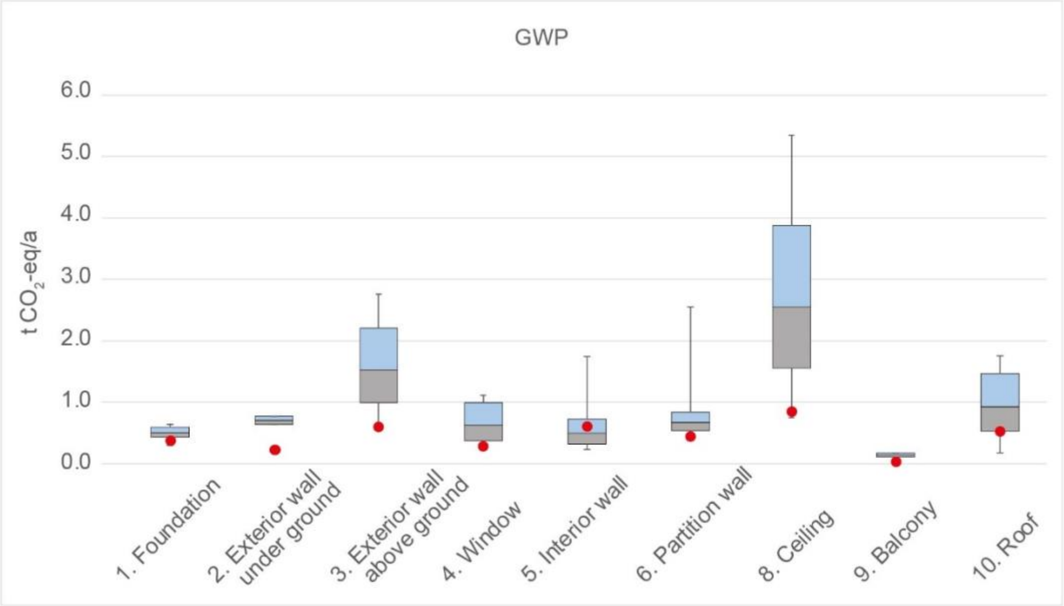

Figure 3. Benchmarks for the individual elements considering the surface areas of the building (points indicate the value for the specific material chosen in the case study)

For the *balconies* and the *exterior walls underground,* the specific values are smaller than the minimum values from the component catalogue. The specific balcony is made of wood, but only concrete is included in the component catalogue. For the *exterior walls underground*, the minimum is calculated including an exterior cladding and insulation for the wall. In the case study, the basement is not heated and therefore no insulation is included. As all selected solutions are close to the minimum, only the interior walls and the roof show a potential for improvement. Assuming the material of the internal walls could be exchanged to meet the benchmark this would save 289 kg CO_2-e/a. Doing the same for the roof would save another 9 kg CO_2-e/a. This means that the optimization of the material could save 298 kg CO_2-e. It is close, but not enough to reach the top-down target for the embodied part. Only, if the solutions with the minimum values are selected, the case study building achieves an embodied GWP of 4779 kg CO_2-e/a and the top-down benchmark is met. However, it is not clear whether this is technically feasible. Therefore, savings other than material optimization are needed. In this case study, the optimization potential of the building’s shape is limited, because the building is very compact. One way to meet the top-down benchmarks is following a sufficiency strategy. If the floor area per resident can be reduced by 15% in this case study, for example through a higher efficiency of the floor plan, shared spaces or other design options, the top-down benchmark can be met.

Target values provided by certification systems and current national standards are usually based on the floor area (either the net floor area or the energy reference area). SIA 2040 currently provides targets for the so-called intermediate goal for the year 2050 which corresponds to total GHG emissions of 2 t CO_2-e/(c·a). Adapting these values to the goal of 1 t CO_2-e/(c·a) results in a target value of 6 kg CO_2-e/(m^2·a) for the sum of embodied and operational GWP. The DGNB target value for embodied GWP only is already 6.6 kg CO_2-e/(m^2·a) for residential buildings. The target value for the operational GWP in the DGNB-system is based on a reference building and is dynamic. Nevertheless, this shows that the current target values are too high to meet the "below 2 degree target" assuming a 1 t CO_2-e/c society. The case study building shows an embodied GWP of 5.0 kg CO_2-e/(m^2·a) and a total GWP of 6.9 kg CO_2-e/(m^2·a). A reduction of 15% is needed to meet the adapted SIA 2040 target. As such, the outcome of using the target values per floor area is similar in this case. However, the target per floor area does not allow to consider sufficiency strategies such as reducing the amount of floor area per resident. Therefore, a benchmark per capita is recommended here in addition

Finally, a building is more than a sum of its building components. As such, there are interdependencies between different components, for example load-bearing exterior or interior walls. Next to the embodied impact, the choice of materials and construction types influence many other building performance criteria. The presented approach is therefore an estimation in early design stages to provide guidance based on the currently available data.

5. Conclusion and outlook

As LCA is more commonly applied to assess the environmental performance of buildings, different actors have a need for LCA-based benchmarks. Investors, building owners and public funding institutions need them to define environmental performance targets and architects need them for design guidance. This paper shows how top-down and bottom-up benchmarks can be combined to provide design guidance. The top-down benchmark is based on the overall target of limiting GHG emissions to 1 t CO2-e per capita and year. The bottom-up benchmarks are statistically derived from typical building components for new residential buildings in Switzerland and the market share of different building materials following a best-in-class approach. A method for using this dual benchmark approach in the design process is proposed. The workflow suggests to first calculate the environmental performance target for the building based on the top-down benchmarks. Then the environmental impact of the building is calculated and it is checked whether the top-down benchmark can be met. If not, the impact of the individual building elements is calculated and compared to bottom-up benchmarks to indicate the material-related optimization potential. Depending on the result, decisions to change the material or the design parameters are taken. Differentiating between material and design-related options provides guidance on how to optimize the environmental performance of the building and its components efficiently. Of course, the approach can also be applied to reduce the impact, if the global target is met by the initial design. The method of using the dual benchmark approach in a case study of a multi-family house showed that the method is applicable. As such, the proposed approach can facilitate using LCA as a design-supporting method in design practice and promote environmental performance optimization of buildings.

Here, the method was applied for new residential buildings. The same method can be adapted to non-residential buildings as well as retrofit projects. The benchmarks should be regularly updated with the latest data. Furthermore, the benchmarks should be implemented into LCA tools applied during design to provide direct feedback on the optimization potential to decision makers. The proposed approach should be developed further including multi-criteria design decisions. In this paper, a top-down target for lifecycle-related GHG emissions has been used. In the future, the approach could be extended to include other environmental impacts besides climate change. The planetary boundary framework [26] could provide a basis for deriving additional target values for buildings. This will lead to a system of benchmarks. Furthermore, the dual benchmark approach could be linked to concepts such as “absolute sustainability” based on the carrying capacity of the ecosystem [27]. This would make sure that measures to lower the GHG emissions due not cause higher impacts in other categories. In the future, the method can also be transferred to other countries to derive national benchmarks for material-related environmental impacts as long as a building component catalogue and market share data are available.

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