Product Resource and Climate Footprint Analysis during Architectural Design in BIM

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Abstract. Significant global economic growth in the building sector is recently being noticed according to cities developments. Buildings and construction materials dominate the increasing demand for natural resources, greenhouse gas emissions, and landfill space. This article assesses the application of the product footprints for material, energy, and water as well as the product climate footprint for different design alternatives of building elements. The alternatives include different designs of foundations, exterior walls, and ceilings using recycled aggregates for concrete production. The approach is assessed cradle-to-gate within the life cycle assessment (LCA) boundaries for building elements and construction materials using a product resource and climate footprint analysis. The material footprint is determined by the indicators Raw Material Input (RMI) and Total Material Requirement (TMR), and the energy footprint by the Cumulated Energy Demand (CED). The water footprint is defined using the Available Water Remaining (AWARE) method. The climate footprint is quantified by the indicator Global Warming Impact (GWI) using Global Warming Potential (GWP) values from the Fifth Assessment Report of the IPCC. The LCA calculation is integrated into a building information modeling (BIM) tool to make changes in footprint results visible to planners, architects, and civil engineers. Results show that material footprint could be significantly decreased when the recycled aggregates are considered to produce waterproof concrete of foundation and underground exterior walls.

1. Introduction

Reaching the Sustainability Development Goals (SDGs) will significantly depend on the construction and real estate activities [1]. Building industry has also an important economic potential to reduce global greenhouse gas (GHG) emissions by 2050 [2]. Most of the GHG emissions from buildings are due to energy consumption, which is either from building usage or construction [3]. Material and water resources are significantly consumed by the construction of buildings [4,5]. Therefore, use of recycled materials and new technologies and innovative designs are increasingly considered for the sustainable built environment [6–8]. Furthermore, future buildings and infrastructure projects could mitigate climate change e.g. by using innovative construction materials, new technologies, or new systems that could contribute to climate footprint mitigation [4,9]. At an early design stage of buildings, enhancing building designers with environmental information about different solutions is an important key to reduce environmental pressure of buildings [10,11]. Life cycle assessment (LCA) is defined as an adequate approach for quantifying environmental impact of buildings [12].
Research on the LCA of buildings has been restricted to limited impact assessment methods, which are mainly related to output impacts [13]. Resource categories such as material, energy, and water are less discussed [14]. This article assesses different design scenarios of building elements within cradle-to-gate LCA boundaries using the product material, energy, water, and climate footprint. The main objective is to provide an approach for building designers to enhance their decisions related to material and design specifications during design stage of buildings. Supporting design teams with information about environmental impact of construction materials could promote building’s design also from low energy building to positive environmental impact building [15]. This approach is mainly studied to contribute towards achieving SDG 9, 11, and 12.

2. Materials and Methods

2.1 System description

Two design options are considered for three selected building elements of a case study. The analyzed building is the town hall of Korbach (Germany), which has been demolished and planned to be built in a sustainable environment way. LCA is done according to ISO 14040 and ISO 14044 [16,17]. The analyzed building elements include foundation, under-ground exterior wall, and ceiling. However, those elements are not representing the whole structure of the building, the same methodology could be considered for the remaining building elements. For each element, two design alternatives are proposed by the architect and compared regarding the use of material, energy, and water as well as GHG emissions within LCA boundaries cradle-to-gate as described in EN 15978 [16-18].

A functional unit (FU) is defined as the value of the functionality of a product or a service [16]. Therefore, one square meter of the building element is considered as the FU. The both design alternatives provide identical services in terms of structural technical requirements, thermal transmittance (U-value) and water-resistance. openLCA software [21] is used with ‘GaBi Professional database’ and the ‘GaBi Extension database XIV: Construction materials’, released 2019 (service pack 38) [22,23] for the life cycle inventory (LCI) modeling.

Additionally, a Building Information Modelling (BIM) concept is used to integrate the footprint results of the LCA into the building design model. The results are integrated into Revit software as new parameters under the properties window of building elements by their relevant indicators. Revit software is a multidisciplinary BIM software from Autodesk (www.autodesk.com), This approach will provide the environmental performance of each design alternative to the planners within the same modeling tool. Usually, building elements i.e. BIM objects are represented only by the model and its technical information. The same methodology could be used to enhance BIM objects to display their environmental information.

2.2 Product Resource and Climate Footprints

The two indicators Raw Material Input (RMI) and Total Material Requirement (TMR) are considered for defining the product material footprint [14,24]. RMI calculates the cumulative used raw materials and TMR accounts for all primary materials extracted from nature, including both used and unused materials. DIN EN 15643-2 [25] declared that material resource use (here defined as product material footprint) should be addressed by indication of primary raw materials taken from the environment. This issue is addressed by RMI. The RMI is already part of the official reporting to assess the material footprint of the German economy [26]. The German Association of Engineers (VDI) describes the Cumulated Raw Material Demand – which may be regarded as a variant of RMI - in the VDI guideline 4800 part 1 and part 2 [27,28].

The Cumulative Energy Demand (CED) [29] is used for determining the product energy footprint, which refers to the lifecycle wide primary energy consumption from non-renewable resources. The AWARE (Available Water Remaining) method [30] is used to quantify the product water footprint. AWARE addresses the potential vulnerability of a catchment area to water stress. It is used to determine the amount of water remaining in a catchment area or in a country less than the water requirements of
humans, animals, and plants. Product climate footprint is assessed by the Global Warming Impact (GWI) according to the values of Global Warming Potential with a time horizon of 100 years (GWP\(_{100}\)) published by the International Panel of Climate Change (IPCC) [31].

2.3 Description of the building elements

Material and technical details of the building elements alternatives are shown in Table 1. For the design alternatives, the use of recycled aggregates from the old building is considered for concrete production (RC-concrete). Percentage of recycled aggregates to all aggregates in the RC-concrete is 35 % for each of foundations and exterior walls and 45 % for ceilings. This percentage is depending on the area of application and the exposure class of the building element, besides according to the type of recycled aggregates corresponding to DIN 4226-101[32]. LCA of the production of recycled aggregates is studied from the end-of-life (EoL) phase, demolishing of the old building, transport of the concrete rubbles to the recycling plant and treatment of the concrete rubbles in a mobile recycling plant, to the production phase (A1-A3) of concrete. Different types of cement are considered for concrete production to testify the consequent environmental performance. Waterproofing characteristics of RC-concrete is additionally considered as an alternative for conventional concrete (C25/30) for the foundation and underground exterior walls. Requirements of waterproof concrete are described in DIN 1045-2 and DIN 206-1 [33,34] with a maximum 0.55 water-cement ratio.

| Material | Thickness [mm] | Quantity [kg/m²] | Foundation | Exterior wall | Ceiling |
|----------|----------------|------------------|------------|---------------|---------|
| Bitumen sheets (2 layers) | 10 | 10.4 | * | * | |
| Carpet tiles | 6 | 4.2 | * | * | |
| Cement screed | 60 | 90.0 | * | * | |
| Cement screed | 77 | 115.5 | * | * | |
| Cement screed (polished) | 60 | 90.0 | * | * | |
| Chipboard | - | 0.2 | * | * | |
| Concrete C12/15 | 50 | 121.0 | * | * | |
| Concrete C25/30 a | 250 | 581.0 | * | * | |
| Concrete C25/30 a | 280 | 663.0 | * | * | |
| Dimpled polyethylene sheet | 9 | 1.2 | * | * | |
| Expanded glass | 630 | 81.9 | * | * | |
| Expanded glass | 650 | 84.9 | * | * | |
| Expanded polystyrene | 80 | 2.1 | * | * | |
| Expanded polystyrene | 160 | 5.1 | * | * | |
| Extruded polystyrene | 10 | 3.5 | * | * | |
| Linoleum | 3 | 3.0 | * | * | |
| Mineral wool | 50 | 0.6 | * | * | |
| Polyethylene | - | 0.2 | * | * | |
| Reinforcing rebar steel b | - | - | * | * | |
| Rubbles 16/32 mm | 150 | 223.0 | * | * | |
| RC-concrete C25/30 with CEM III 42.5 | 250 | 558 | * | * | |
### 3. Results and Discussion

The results for the product material footprint measured in RMI and TMR are shown in Figure 1.

![Figure 1. Product material footprint in terms of raw material input (RMI) measured in kg raw material and total material requirement (TMR) measured in kg primary material per m² of the design alternatives of foundation, exterior wall, and ceiling.](image)

RMI and TMR are decreased by up to 35% for the second design alternative of foundation. This is mainly because of using recycled aggregates to produce RC-concrete with waterproofing characteristics. The use of crushed rock (16-32 mm) for filling under foundation increases RMI and TMR, which could be replaced with recycled aggregates with filling properties from the old building.

However, the material footprint is highly reduced mainly according to use of RC-concrete, other considered footprints are not significantly influenced (see Figure 2). This is because e.g. product climate footprint of concrete is mainly influenced by cement production. The manufacturing of steel rebar is dominating the product energy, water, and climate footprints. Other possible reinforcing options of concrete such as steel fibers could provide a better environmental performance [19]. Trade-off between different footprint categories is shown for the design alternatives, which could be further enhanced with normalization [36] for optimizing the best architectural design in terms of product resource and climate footprint.
Figure 2. Product water footprint (a), product energy footprint (b), and product climate footprint (c) per 1 m² of the alternatives for foundation, exterior wall, and ceiling.

In Figure 3 the exterior wall alternative (E1) is shown in the BIM software Revit. The results could be considered by the building planners to improve the environmental performance of the building design. The approach could be followed by the manufacturers of construction materials, who are presenting their products as BIM objects [37]. This could give the building planner and architect an initial image about the environmental performance during design stage of the building. However, an additional tool is needed for the interoperability requirements of changings design, to provide a real-time footprint analysis of different building design alternatives [11].

Figure 3. Building Information Modelling (BMI) software Revit showing the product resource and climate footprints per 1 m² of the exterior wall (Note: RMI: Raw Material Input, TMR: Total Material Requirement, CED: Cumulative Energy Demand, GWI: Global Warming Impact)
4. Conclusion
The article provides the product resource and climate footprints results of different design alternatives of building elements based on cradle-to-gate LCA. The calculation is combined with a BIM tool to allow the optimization of the environmental performance in the design phase of buildings. The approach shows a possible linkage between buildings and footprint data practitioners. It allows presenting footprint data of building components together with the technical details of construction assemblies. There is abundant room for further progress in determining the resource and climate footprints in the use phase of buildings, and in improving the footprint analysis using BIM software solutions.

Acknowledgment
The research is funded by the German Federal Ministry of the interior, building, and community (Forschungsinitiative Zukunft Bau) under grant agreement SWD-10.08.18.7-.18.20. Many thanks to: architect Ms. Anja Rosen for providing all the details needed for the design options, Ms. Dilan Glanz for cooperating in doing LCA of RC-concrete, Ms. Kathrin Frey for collecting LCA data, Mr. Guillaume Behem for doing the building model in Revit software, and the anonymous reviewers for their constructive comments.

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