Ecological performance and recycling options of primary structures

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Abstract. A sustainably and optimally building material is defined consequently in a well-balanced relation between ecological aspects and structural engineering requirements and should be selected depending on external conditions. By choosing environmentally friendly building materials and joining techniques, at least resource-efficient and sustainable construction can be achieved. As a contribution to the discussion about which building materials offer the most optimal and environmentally friendly properties for the construction industry, this paper gives an overview of sustainable construction. It illustrates the advantages and disadvantages of certain building materials and structural components by comparing their mechanical properties and ecological aspects using various types of life-cycle assessment (LCA). As far as construction materials are concerned, e.g. wood-based materials have the greatest potential in terms of renewable primary energy demand compared to all other constructions materials. Furthermore, due to the high recycling potential, wood has the lowest share of non-renewable primary energy demand, whereas the highest non-renewable primary energy demand is caused by mineral building materials. This paper illustrates how the natural resources can be used both optimally and sustainably. It presents a conceptual framework for scenario development of the LCA of primary structures, their effect on the design and decision-making process.

1 Introduction

2017 greenhouse gas (GHG) emissions in Austria have risen for the third time in succession (cf. Figure 1-1). With 51.7 million tons CO₂-equivalent (not including any emission allowances from the European Union Emissions Trading System) the national goal was initially exceeded. In total, emissions rose to 82.3 million tons, which equates to a 3.3 % increase compared to 2016. This is due to the increased usage of fossil fuels in the energy and industry sector (plus 5.4 %) as well as the increased demand for the transportation of goods. Also the emissions attributed to the transportation and building sector have noticeably risen. On the contrary, the waste management industry and agricultural sector recorded falling emissions compared to 2016 [1].

![Figure 1-1 Greenhouse emissions in Austria from 2013 to 2017 [1]](image-url)
1.1 State of the Art
An integral part of the European energy strategy is the increase of power efficiency. On one hand, the European council demands a 20% reduction of greenhouse emissions by the year 2020, compared to 1990 and a 20% share of renewable energy of the final energy consumption throughout the European Union. On the other hand, an increase of power efficiency is being demanded, so that the initial value for 2020 is undercut by 20% [2].

Particularly in the building sector, the focus lies on residential building. As a whole, residential buildings hold a high proportion of energy usage in this sector. But, thanks to the stricter requirements on new constructions in the past two decades and the reinforced funding conditions, the emissions induced by heating the buildings stayed relatively constant from 1990 to 2003 [2].

Nowadays the required energy standard of buildings according to building regulation is at the level of a low-energy house. By introducing the “Energy Performance of Buildings Directive”, the European council established the basis for uniform valuation. These guidelines indicate that a building has to be sustainable, the used construction materials and components have to be recyclable and the use of environmentally friendly resources and secondary materials is welcome [2].

1.2 Deconstruction and recyclability
Recycling means employing the materials used for the construction and operation of a building after the initial use for a new purpose [3]. Waste products turn into secondary raw material. Easier dismantlability of an object into its components means that this object shows a better deconstruction [4]. Already in the planning stage of construction projects (cf. Table 1-1), recyclability of the materials has to be considered. Preferably, recyclable components or already recycled components should be used. In Table 1-1 the life cycle phases of a building are classified.

| Life cycle phases of a building | Additional information outside of the life cycle |
|--------------------------------|-----------------------------------------------|
| A1-3 Product stage | A4-5 Construction stage | B1-7 Use stage | C1-4 end of life cycle | D advantages and liabilities outside of the system boundaries |

| A1 Raw material supply | A2 Transport | A3 Manufacturing | A4 Transport to construction site | A5 Installation at construction site | B1 Use | B2 Maintenance | B3 Repair | B4 Replacement | B5 Refurbishment | B6 Operational energy use | B7 Operational water use | C1 De-construction and demolition | C2 Transport | C3 Waste processing | C4 Disposal | Potential of reuse. Recycling and energy recovery |
|------------------------|-------------|----------------|---------------------------------|-------------------------------|-------|--------------|----------|----------------|-----------------|--------------------------|---------------------|--------------------------|-----------|----------------|------|---------------------------------|

The following factors concerning the recyclability should be considered [4]:

- **Homogeneity**
  Used building materials should be as homogenous as possible. The less different the materials are, the less differentiated the waste management is [3].

- **Separability**
  Material compounds which are easily separable, are ecologically valuable. Easily detachable materials increase the probability of a pure division and the recirculation into the substance flow [3].
Absence of pollutants

The use of building materials, that are harmful for the environment and the people, is being significantly reduced in sustainable construction. Moreover, the diligent use of unpolluted recyclable building materials optimizes the economic efficiency of the materials cycle and prolongs the material’s lifespan [3].

The lifecycle of the construction alternatives is being analyzed according to EN 15978 “Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method”. [6]

2 Life cycle assessment indicators

For the life cycle assessment of building materials, the following indicators are being calculated based on the German Sustainable Building Council (DGNB) [7]:

- Primary energy content PEIn, PEI [MJ]
- Global warming potential GWP [kg CO2 – eq] calculated over a time horizon of 100 years
- Acidification potential AP [kg SO2 – eq]

3 Systematic analysis of the environmental impact of building materials

The ecological attributes of the compared building materials originate from “IBU-EPD” [8], a standardized database for ecological evaluations by the Federal Ministry of Interior, Building and Community in Germany. Most of the available data refers to the life cycle phase A1-3 “production phase” (cf. Table 1-1).

Figure 3-1 shows the environmental impact of wood (oriented strand board, solid structural timber, medium density fiberboard) compared to bricks (insulating and non-insulating) and concrete (different classes of compression strength). The data indicates the environmental impact per m³.

![Figure 3-1 LCA indicators of building materials per m³ for the “production phase” A1-3](image)

Generally speaking, wood has relatively high primary energy content values in the production phases A1-3 (c.f. Figure 3-1). Nevertheless, compared to the other building materials most of the primary energy content is renewable. Bricks with a density of 740 kg/m³ have better environmental effects than those filled with pearlite (density 800 kg/m³). However, with the non-insulating bricks, an insulation layer with relatively high environmental impacts will most probably be needed later on. The environmental impacts of concrete
increase with the compression strength. Concrete C25/30 therefore causes the least environmental effects whereas concrete C50/60 causes the most.

4 Structural elements

The ecological values of the compared structural elements also originate from “IBU-EPD” [8]. To ensure comparability all values are referenced to 1 m² of the component. The period of observation is 100 years and all life cycle phases, including phase D „advantages and liabilities outside of the system boundaries“ are considered (c.f. Table 1-1). Furthermore, the structural elements were calculated referring to the location of Vienna.

4.1 Intermediate floors

Comparing the different versions of intermediate floor structures (c.f. Figure 4-1), it is noticeable that concrete structures have the lowest renewable primary energy consumption but nevertheless the highest non-renewable primary energy consumption. In contrast, timber floors have the highest potential in renewable primary energy consumption, while in most cases having negative non-renewable primary energy consumption values, which counts as a credit for the rest of its life cycle.

![Figure 4-1](image)

**Figure 4-1** LCA indicators of intermediate floors (only constructions) per m² for the life cycle phases A-D.

4.2 Intermediate floors including floor assemblies

Concrete structures have a relatively low primary energy demand, but have the highest non-renewable primary energy demand (c.f. Figure 4-2). Especially, the T-Beam floor with cement screed and laminate has outstandingly high values. By comparison, wooden floor structures have the highest potential for renewable primary energy demand and, in most cases, have negative values for non-renewable primary energy demand, which can be counted as a credit for the further life cycle. An example for this is the solid timber floor with cement screed and stoneware tiles.

![Figure 4-2](image)

**Figure 4-2** LCA indicators of intermediate floors incl. floor assembly per m² for the life cycle phases A-D.
4.3 Flat roof structures
Comparing the entire flat roof structures (c.f. Figure 4-3), it is noticeable, that the classic inverted roof has the highest ecological values in every aspect. The conventional warm roof performs the best. Merely the renewable primary energy consumption values are the same for all three roofs.

![Figure 4-3](image)

**Figure 4-3** LCA indicators of flat roof structures (only construction) per m² for the life cycle phases A-D.

4.4 Flat roof structures including finished components
As shown in Figure 4-4, the classic inverted roof has the highest environmental impact in every aspect. A standard warm roof has the lowest values in all categories. Only in the case of the values for the renewable primary energy demand, the flat roof structures hardly differ. However, with regard to the roof construction it is noticeable, that the values of the individual roofs have become more similar.

![Figure 4-4](image)

**Figure 4-4** LCA indicators of flat roofs including finished components per m² for the life cycle phases A-D.

4.5 Opaque external walls
As shown in Figure 4-5, the renewable primary energy consumption values for brick and concrete walls in opaque external walls are the lowest, while their non-renewable primary energy consumption values are the highest. Timber constructions on the other hand perform better.
Figure 4-5 LCA indicators of opaque external walls (only construction) per m² for the life cycle phases A-D.

4.6 Opaque external walls including wall assemblies

Brick and concrete structures have the lowest values for the renewable primary energy demand, but the highest values for non-renewable primary energy demand. (c.f. Figure 4-6) Particularly, the reinforced concrete monolithic wall has a significantly higher primary energy demand than the other mineral wall structures. Timber constructions on the other hand perform better in this respect. Similar to intermediate floors, timber constructions consume a significantly lower amount of non-renewable primary energy.

Figure 4-6 LCA indicators of opaque external walls including assemblies per m² for the life cycle phases A-D.

5 Case study

The case study consists of following components: the building site is in the yard of the main building of the Vienna University of Technology at the 4th municipal District of Vienna, Austria. The floor area of the building is 24 x 24m and is planned with two upper floors and a punctuated façade. The number of floors was chosen to give the investigation the best possible conditions. The total height of the building is 9.55 m, the floor height is 3.10 m and the clear room height is 2.70 m. The room has a floor area of 9 x 5.5m, is strained on one side and has a span width of 5.5m. The exterior design of the building (Figure 5-1) is a punctuated façade, which is plastered depending on the building type (bricks, ETICS = external thermal insulation composite systems) or on sight (exposed concrete).
5.1 Optimization of material usage in the construction process

Both sustainability and ecological ideas should be understood as a process. To give an overview of the optimization measures in this process, individual planning strategies and processes are assigned to the generally valid planning phases: preliminary study, competition / preliminary planning, conceptual design / approval planning, tendering and contracting / implementation planning, execution / completion, handover / operation [9].

In the life cycle of materials, attention is paid to the use of resource-saving and environmental friendly building materials, whereas the focus in the building life cycle is on the adaptation of the intended use. In the material life cycle this means: use of permanently available resources, use of building materials with low primary energy consumption, use of pollutant-free and low-emission products, exchange of primary raw materials through recycling material, design optimization of the used components, preparation for reuse [9].

When optimizing use in the building life cycle, the following principles must be observed: adaptation to intended use, adaptation to durability and integration of efficiency enhancing designs, use of recoverable constructions, integration for possible conversion [9].
5.2 Component optimization of the construction model

Based on necessary component optimization, the monolithic construction, both in concrete and in bricks, need more measures to achieve the summer suitability according to ÖNORM B 8110-3 [10] than constructions with a thermal insulation composite system. The concrete performs better within the particular construction. However, the best protection against summer overheating, regardless of building material, is nocturnal ventilation to get the indoor heat out of the room. It can be observed, that with an optimized design, the orientation of the room has little effect on the course of the operative room temperature.

The LCA in Figure 5-2 shows that, among the selected parameters, the non-renewable primary energy consumption has the largest environmental impact. Within the chosen system boundaries concrete constructions tend to produce more environmental effects than brick constructions. For concrete, the monolithic variant has significantly higher environmental impacts than the insulated component, whereas for brick components the insulated brick components cause more environmental effects than the monolithic counterpart.

Overall, the calculations for the external wall reveal significantly greater differences in the component variants than would be the case with intermediate floors or flat roofs.

6 Conclusion

A sustainably and optimally building material is defined consequently in a well-balanced relation between ecological aspects and structural engineering requirements and should be selected depending on external conditions. By choosing environmentally friendly building materials and joining techniques, at least resource-efficient and sustainable construction can be achieved.

In the context of the building there are many aspects to be considered. Building materials are in a functional relationship with each other and with the construction structure. When assessing the overall situation, aspects such as location, climatic conditions, availability of renewable energy sources, user behavior or special need of the client play such an important role that they have to be taken into account when choosing the building materials.

The ecological performance and recycling options of the components are influenced to a great extent by both the choice of construction material and the insulating material, details and the type of construction in general as well as the methods of reusing and recycling them.

By selecting environmentally friendly building materials and joining techniques, at least resource-saving and sustainable construction can be achieved. Legal requirements and minimum standards will make the need to incorporate sustainable criteria into the planning process more relevant in the future. Nevertheless, it can be seen that today the results vary greatly due to different data bases. Each database and rating system is based on different criteria and objectives. Therefore it is advisable to deal with this early in the planning process and to adapt the objectives of the construction planning. Sustainable building planning requires holistic and flexible planning. Long-term thinking and matching the lifespan of building materials with utilization flexibility is essential for ecological construction.
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