Ecological performance of reusable load-bearing constructions

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Abstract. This study provides an overview of sustainable reusable load-bearing constructions as a contribution to the debate over whether building construction provides the building industry with the best and most environmentally friendly qualities. By contrasting their building-specific features, it demonstrates the benefits and drawbacks of particular structural elements and envelope solutions and ecological aspects using various system boundaries of life-cycle assessment (LCA). Following a careful consideration of ecological factors and sustainable circular economy criteria, a structural component that is sustainably optimized is defined. This component should be chosen based on external conditions. By selecting environmentally friendly building materials and proper connecting procedures that enable separability, resource-efficient and sustainable buildings can be achieved. Both the selection of load-bearing elements and the necessary insulating material have a significant impact on the ecological performance and reusability options of the components. The elements of homogeneity, separability, and pollutant-freeness play a significant influence in the reuse process, namely in terms of details and construction type in general, as well as the ways of reusing and recycling them. Sustainable solutions for load-bearing building components can be created by simultaneously investigating environmentally friendly building materials and the structure of the components. 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 load-bearing structures, their effect on the design and decision-making process. There is a potential of increasing total resource efficiency at the building level with a suitable combination of the material components employed at the component level. Because of this, the overall energy efficiency and its consequent ecological impacts are the main topics of this study.

Keywords: Sustainable Architecture, Reuse, Recycling, Reusable Construction, Deconstruction, Reduce, Resource Efficiency, Structural Components

1. Introduction

In the past thirty years, an increasing number of timber-based buildings have been constructed worldwide. In Austria, timber construction has increasingly gained market share over the last twenty-five years. Currently around one quarter of the construction volume in building construction is made of timber. At the residential segment, the proportion of timber construction has risen particularly strong with an increase from 10 up to 23% [1]. Due to these extensive activities, the Vienna University of
Technology's Department of Structural Design and Timber Engineering (ITI) has created a number of wood-based composite systems with the goal of maximizing structural and ecological behavior at both the component and system level [2, 3, 4]. With a special focus on the optimization of both structural and ecological properties of the mentioned construction systems, numerous boundary conditions influence the structure significantly. Therefore, as a result, an environmentally holistic consideration can also only be enabled by focusing on structural characteristics, such as geometrical and mechanical properties, as well as on building physical and ecological characteristics, such as energy and resource consumption, and hence derived aspects. By a suitable use of wood as a renewable raw material combined with other building materials, such statically as well as sustainably effective constructions can be achieved [5].

For this reason, the ecological potential of various developed wood-based construction systems shall be shown and compared to conventional building structures. To reach a maximum holistic assessment of the mentioned systems, the whole life cycle of the structures ("from cradle to grave") is investigated. The Environmental Product Declaration for Building Products in accordance with ÖNORM EN 15804 is the source for the ecological simulation and balancing based on these calculations [6]. All life cycle stages "production" (A1 to A3), "use" (B1 to B7), "end of life" (C1 to C4) and "benefits as well as loads beyond the system boundary" (D) are considered (cf. Table 1). The standardized database for ecological evaluations of buildings ÖKOBAUDAT of the German Federal Ministry for Housing, Urban Development and Building serves as the foundation for all ecological characteristics used in this simulations [7].

2. Computer-based research and modelling

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. According to these regulations, a building should be ecologically friendly, utilized construction materials and components must be recyclable, and using recycled materials is encouraged [8].

2.1. Life cycle assessment indicators

The ecological attributes of the compared building materials originate from the databases “IBU-EPD” [9] and “ÖKOBAUDAT” [10], both standardized databases for ecological evaluations by the Federal Ministry of Interior, Building and Community in Germany. In Table 1 the life cycle stages of a building are classified. Thereby considered assessment criteria are the non-renewable Primary Energy Input (PEIₙ), renewable Primary Energy Input (PEIᵣ) and the Global Warming Potential over 100-year time horizon (GWP₁₀₀) based on the German Sustainable Building Council (DGNB) [11].

2.2. Deconstruction and recyclability

Reusability of the materials must be taken into account throughout the planning stage of construction projects in a dynamic design process. It is best to use recyclable or reused parts whenever possible. Easier dismantlability of an object into its components means that this object shows a better deconstruction [12]. Recycling is the process of using a building's construction and operating elements for a new purpose after their first usage [13], i.e. waste materials become secondary raw materials. The following aspects of recyclability should be taken into account [12]:

- Separability: ecologically useful material compounds are those that are simple to separate. Materials that are simple to separate raise the likelihood of pure division and recirculation into the substance flow [13].
- Absence Homogeneity: It is best if used building materials are uniform. Waste management is less distinct the less varied the materials are [13].
2.3. **Environmental impact assessment of building materials per cubic meter**

The life cycle of the construction alternatives is being analyzed according to EN 15978 “Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method” [14] in consideration of their recyclability potential. The period of observation is 100 years and all life cycle stages (“from cradle to grave”), including stage D (cf. Table 1) are considered. Furthermore, the structural elements are calculated referring to the location of Vienna. Figure 1 compares the environmental impact of wood (oriented strand board, solid structural timber, and medium density fibreboard), bricks (insulating and non-insulating), concrete (different classes of compression strength) and glass panes per cubic meter in all life cycle stages. In general, wood has relatively high primary energy content values, especially in the production stages A1-3. Nevertheless, compared to the other building materials most of the primary energy content is renewable (most of it are the solar gains in the production stage). 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.

**Table 1. Life cycle stages of a building.** [15]

| Life cycle stages of a building | Additional information outside of the life cycle |
|--------------------------------|-----------------------------------------------|
| A 1-3 Product stage            | D advantages and liabilities outside of the system boundaries |
| A 4-5 Construction stage       |                                               |
| B 1-7 Use stage               |                                               |
| C 1-4 end of life cycle       |                                               |
| 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           | Potential of reuse, recycling, and energy recovery |
| C4 Disposal                   |                                               |

2.4. **Analysis of the environmental impact of load-bearing elements**

The components are selected for the comparison by their frequency of use in construction practice. To ensure comparability all values are referenced to 1m² of the component and the load-bearing elements have load-bearing capacity as well as similar thermal transmittance (U-value) in each category. The U-value was chosen as comparability factor because of its importance in modern building practice. Especially in zero-energy buildings or plus-energy buildings the U-values are one of the most important indicators.

2.4.1. **Thermally insulated flat roofs**

In the construction of thermally insulated flat roofs, three variations exist: the twin-skin flat roof (cold roof), the inverted roof and the single skin flat roof (warm roof). Comparing the entire flat roofs (cf. Figure 2), 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. The components are selected for the comparison by their frequency of use in construction practice. To ensure comparability all values are referenced to 1m² of the component and the structural elements have similar load-bearing capacity and thermal transmittance (U-value) in each category.
Figure 1. Life cycle assessment indicators of building materials per m$^3$ for all life cycle stages A-D.

Figure 2. Life cycle assessment indicators of flat roofs per m$^2$ for all life cycle stages A-D.

2.4.2. Flat roofs including finished components
As shown in Figure 3, 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.

2.4.3. Opaque external load-bearing walls
The renewable primary energy consumption values for brick and concrete walls in opaque external walls (without insulation) are the lowest, while their non-renewable primary energy consumption values are the highest (cf. Figure 4). Timber constructions on the other hand perform better, especially in regard of the global warming potential.
Figure 3. Life cycle assessment indicators of flat roofs including finished components per m² for all life cycle stages A-D.

Figure 4. Life cycle assessment indicators of opaque external walls per m² for all life cycle stages A-D.

2.4.4. Opaque external load-bearing walls including finished components
Walls built out of bricks and concrete have the lowest values for the primary energy demand that is renewable, but the greatest values for the primary energy demand that is not renewable. (cf. Figure 5) Compared to other mineral wall structures, particular the reinforced concrete monolithic wall has a much greater primary energy requirement. Timber constructions on the other hand perform better in this respect. The timber constructions consume a significantly lower amount of non-renewable primary energy.
Figure 5. Life cycle assessment indicators of opaque external walls including finished components per m² for all life cycle stages A-D.

3. Case Study

A case study looks at a mix of materials including glass, wood lightweight concrete (WLC), and timber (in the form of integrated timber ribbed panels, or HCLTP components). The potentials for each material have already been recognized in order to improve the overall resource efficiency of the entire construction (cf. Figure 1). The integrated panel and ribbed component geometry of the space-forming carrier material timber in the form of integral timber ribbed panels (HCLTP elements) provides an ideal platform for the execution of a multi-layer polyvalent composite structure when timber-WLC-glass (HCLTP-HGV-L)-façades are utilized (cf. Figure 6, left). A buffer plane can be made in the area between the ribs and stiffening glass elements can be mounted on the outside of the ribs thanks to the ribbed structure. By using an additional adaptive planking made of WLC, this gap can contribute to the structural optimization of the load-bearing structure [16]. In addition, the way in which the individual parts are connected makes them easy to dismantle and allows the individual building materials to be transferred to the reusing and recycling process.

Furthermore, coherences of sustainability and energy efficiency on component and on overall system level can most suitable be shown by the assessment of a building model with a maximum geometrical simplicity. Consequently, a quadratic one-storied simulation model in different variations (wood-based and conventional building structures) is defined, subsequently investigated and compared with regard to its thermal behavior (heating energy demand as well as operative room temperature) and to its resulting ecological impacts (life cycle analysis).

3.1. Thermal simulation

With an adequate combination of the material components there is the possibility of an increase in overall resource efficiency at building level. For this reason, this paper focuses on the overall resulting energy efficiency. For the thermal simulation [17], the framework conditions are defined (cf. Figure 6). Both a static monthly balance sheet approach for calculating the annual heating requirement (according to ÖNORM B 8110-6 Parts 1 & 2 [18, 19], ÖNORM B 8110-3 [20], ÖNORM EN ISO 52016-1 [21] and ÖNORM EN ISO 52017-1 [22]) and a thermal dynamic calculation method for determining the operating room temperature serve as the foundation for the calculation concepts. The simulation takes place in Vienna (inner city) at an altitude of 164 meters, on July 15, 1:00 PM. The average temperature
±7K is 24.9°C. The reference room has the dimensions 8m x 8m x 3m, with a HCLTP-HGV-L façade as shown in Figure 6. Because the floor and slab, which all four walls abut upon, are non-adiabatic, the adjacent rooms above and below have distinct thermal conditions from the room itself. In addition to the 2W/m² heat output from lightning and equipment, a permanent resident with an internal load of 90W is also anticipated. A value of 0.1h⁻¹ indicates the infiltration rate.

Figure 6. Basic idea of the combination of timber-WLC-glass façades (left) and isometric view of the simulation model (right) [17]

The proportion of windows that can be opened is 74% (cf. Figure 6, right). The reference façade alludes to a completely transparent building envelope. All window variations try to stay in the same grid, therefore unusual sizes occur. In all variations, natural night ventilation through the windows is provided from 08:00 PM - 08:00 AM. The structure of the building components, as well as the different window arrangements, is shown in Figure 6, right. The results of the thermal simulation can be seen in Figure 7. Table 2 shows the variants with values exceeding the maximum operative room temperature of 27°C. The variant GFV1 with 74% window share 5 windows in the façade (cf. Figure 6, right) clearly exceeds the 27°C limit from 11:00 AM. on the selected day, as the room heats up due to the strong solar radiation with such a large proportion of windows. As an opposite approach, the variant GFV4 with a window proportion of 15% with 2 windows was chosen (cf. Figure 6, right). In this case, the reverse is true, since the proportion of solar radiation entering the room is significantly lower. This means that the limit of 27°C required by ÖNORM B 8110-3 [20] is not exceeded in summer. With variant GFV5 including additional external sunblind (cf. Figure 6, right) it was proven that even with a 74% window proportion, a high thermal performance can be achieved in the reference room with the help of external sun protection.

In summary, it can be stated that a very low proportion of windows can also mean lower temperatures. However, the GFV3 scenario also shows that temperatures do not necessarily decrease linearly with a smaller window area, but that the ratio of opaque to transparent façade plays a role, especially if natural night ventilation through the windows is assumed. The optimum ratio turns out to be a window-to-façade ratio of about 29% to 71%, with maximum temperatures of 26.6°C being reached.
3.2. Ecological impact

For a holistic ecological assessment of building structures, the same framework conditions are applied as in the previous investigations. With these environmental computations, the ecological properties and impacts of wood-based construction systems can be shown. Furthermore, decisively design criteria for sustainable structural systems can be derived thereof.

The ecological evaluation is based on the 5 variants and the relation of the ratio of transparent and opaque surface to the reference façade. Since the values are calculated for the entire reference façade as well as for 1 m² of façade including the window portion, conclusions can be drawn at the building material level and in the installation variants. Table 2 shows the structure of the investigated components.

The calculations for 1 m² of façade initially show the ratio of the environmental impact of the façade and the windows or windows with external sun protection. The environmental impacts of windows per m² are significantly high for PEl (total non-renewable primary energy) and GWP (global warming potential). In addition, the environmental impacts of the windows are doubled if an external sun protection system is also installed, which is due to the additional material in the form of steel and aluminum. The reuse and recycling existing windows and their contents in the same form are as well assumed.

Since the values are calculated for the entire reference façade as well as for 1 m² of façade including the window portion, conclusions can be drawn at the building material level and in the installation variants. The results are shown Figure 8, Figure 9 and Figure 10.

Table 2. Structure of the components incl. factor (=weight of components per m²) [17]

| Material                        | Factor [kg/m²] |
|---------------------------------|----------------|
| Plasterboard 2 ply              | 17             |
| 3-layer cross laminated timber, | 56.7           |
| Wood lightweight concrete       | 24.9           |
| Standard plaster                | 12             |
| Glued laminated timber          | 5.11           |
| Laminated veneer lumber         | 0.9            |
| Silicone                        | 0.75           |
| Blocking                        | 0              |
| Sealing PE                      | 0.01           |
| 25 insulating glass g=0.62      | 21.13          |

Figure 7. Results of the thermal simulation (operative room temperature) [17]
Figure 8. Renewable primary energy demand for the variants GFV1-5 [17]

Regarding the non-renewable primary energy demand PEI$_{ne}$, the variants GFV2 and GFV4 have the lowest PEI$_{ne}$ values due to the higher proportion of façade and the associated credits (module D) and low PEI$_{ne}$ values of the installed timber products (cf. Figure 9). In contrast, the highest values for the non-renewable primary energy requirement PEI$_{ne}$ are determined for the other three variants. By far the highest PEI$_{ne}$ values are also obtained for the GFV5 variant, which be attributed to the materials used for external sun protection.

Figure 9. Non-renewable primary energy demand for the variants GFV1-5 [17]

The conclusions from the calculations for the global warming potential of the variants are similar to those for the non-renewable primary energy demand (cf. Figure 10). The variants GFV1, GFV3 and GFV5 are identified with the highest GWP values, with GFV5 again showing by far the highest values.

Figure 10. Global warming potential for the variants GFV1-5 [17]
The lowest values due to the low proportion of windows can be observed for the variants GFV2 and GFV4. In principle, relatively high credits can be identified in all variants except GFV5 due to the high proportion of timber. In summary, the variants with an increasing proportion of windows show increasing values for non-renewable primary energy demand and global warming potential. It should be noted that under the given conditions the GFV2 variant stands out in particular. This variant with a 29% window proportion results in an optimum ratio of transparent and opaque façade, which means that a high thermal quality in the interior of the building within the limits of the [20] can be achieved. Furthermore, the effects of additional external sun protection on PEI_{ec} and GWP are significant.

4. Conclusions
In a progressive design process, reusing and recyclability of the materials has to be considered in the initial design stage. The ecological performance and recycling possibilities of all components are influenced to a great extent by the choice of both load-bearing construction material and insulating material. Environmental impacts of building structures are related to a large variety of various boundary conditions. To enable quantitative statements regarding the environmental efficiency of building structures, a simple spatial simulation geometry in different structural variations is defined and investigated with regard to the respective life cycle sustainability. From an ecological point of view, if the aim is to minimize the "grey energy" (PEI_{ec}), variants with the lowest possible proportion of glass are clearly preferable. The computational studies also demonstrate that timber-based structural solutions can substantially improve a building's ecological effect by meeting modern technical requirements. The greatest way to achieve resource-saving and sustainable construction is to choose environmentally friendly building materials and joining methods. However, it is clear that today's results vary significantly because of various data bases. Each database and rating system is founded on a unique set of standards and goals. The thermal simulations show that considering the opening ratios in buildings - natural night ventilation through the windows - clearly preference should be given to variants that either have external sun protection or the smallest possible window areas. However, in the case of small window areas, an adequate ratio of window and façade areas must be ensured once natural night ventilation through the windows is assumed. If the window areas are too small, natural night ventilation can become ineffective. Thus it is necessary to address this early in the design process and modify the construction planning's goals. Planning for sustainable buildings demands flexible and comprehensive planning. For environmentally friendly construction, long-term planning and combining the durability of building materials with flexibility in usage are crucial. Legal requirements and minimum standards will make the need to incorporate sustainable criteria into the planning process more relevant in the future.

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