Life cycle assessment of wood construction according to the normative standards

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Abstract

This study demonstrates life cycle assessment (LCA) on a reference wooden building according to the latest normative standards: EN 15804, EN 15978 and EN 16485. Through the assessment, application of the standards was studied. In addition, proposals for further development of the standards, especially concerning wood products and wood construction, are discussed from a practical perspective.

Lack of proper data is critical issue in conducting the assessment in compliance with the standards. Since LCA is data-intensive method, preparation of data for the building assessment according to the standard is urgently required. This paper also raised the questions about the provisions in the standards and insisted the importance of the communication system of the assessment results. It would be of importance to develop the communication system in such a way as to stimulate the environmental- conscious in society. In order to develop a relevant communication system, further discussion and case studies would be important and feedback from such practices should be incorporated into the development of the guideline for the assessment.

Abstract

In dieser Studie wird eine Ökobilanz für ein mehrgeschossiges Holzgebäude unter Berücksichtigung der aktuellen Normen EN 15804, EN 15978 und EN 16485 dargestellt. Mit der Berechnung wird die Anwendbarkeit

der Normen untersucht. Zusätzlich werden mögliche Aspekte einer Weiterentwicklung der Normen, die hauptsächlich die Holzprodukte und Holzkonstruktionen betreffen, aus Anwendersicht beleuchtet.

Eines der größten Probleme bei der Durchführung dieser Berechnungen war es Datengrundlagen, die den Normvorgaben entsprechen, zu finden. Da Ökobilanzierung von der Qualität der Eingangsdaten abhängt, sind Datengrundlagen, die den Normen entsprechen dringend nötig. Diese Studie warf auch die Frage nach konkreten Vorgaben in den Normen auf. Sie stellt die Wichtigkeit einer einheitlichen Darstellung der Ergebnisse dar. Es ist notwendig, die Kommunikation der Ergebnisse zu vereinheitlichen und das Umweltbewustsein der Gesellschaft anzuregen. Weitere Untersuchungen und Diskussionen von Referenzgebäuden für verschiedene Aspekte sind hierzu notwendig. Rückschlüsse aus diesen Untersuchungen sollten in die Entwicklung eines Leitfadens zur Erstellung von Gebäudeökobilanzen aufgenommen werden.

1 Introduction

The building sector is recognized as being a major contributor to the overall environmental impact of Humankind's activities. For instance, the sector accounts for about 40% of total primary energy consumption in the European Union (EC 2007) with the associated, and severe, environmental impacts. In the context of sustainable development, a reduction in the environmental impact of a building during its life cycle would be highly desirable. Quantifying and understanding environmental impact has been used in assessing the sustainability of buildings since 1990 (Fava 2006) and numerous studies relating to building life cycle assessment (LCA) have been carried out internationally.

At first, attention was mainly focused on analysing the operation phase of buildings, since it has been stated that in many cases this accounts for more than 70% of the life cycle energy use of a building (Fay et al. 2000; Ortiz et al. 2009; Passer et al. 2012; Verbeeck and Hens 2007). As a result of efforts aimed at reducing the operational energy demand, the environmental impact from the use phase has been mitigated and the relative importance of the other life cycle stages has increased (Verbeeck and Hens 2007). For instance in nearly Zero Energy Buildings (nZEB), the impact from the production and construction phase account for 50% or more of the total life cycle impact (Hafner et al. 2012). Thus interest in the other life cycle phases of buildings has increased significantly (Dodoo et al. 2009; Venkatarama Reddy and Jagadish 2003; Thormark 2006).

In this context, the comparability of results has also recently been highlighted as a future challenge (Allacker et al. 2013; Wittstock et al. 2013) since in practice uncertainties are inherent in LCA. Furthermore, LCA is a data-intensive method, and the results vary on a case-to-case basis with different methodologies being applied depending upon according to the purpose of the assessment (Peeredoom 1999; Erlandsson and Borg 2003). Thus normative standards have been developed aimed at harmonizing the assessment methodologies. The state-of-the-art standards EN15804 (2012) and EN15978 (2011), developed by the Technical Committee TC 350 of the European Committee for Standardization (CEN/TC 350), provide frameworks for the assessment of building products and buildings. The standards are based upon the philosophy of a linear building life cycle (Fig. 1) consisting of four main stages (module A1–3: Product stage, A4–5: Construction process stage, B: Use stage and C: End-of-Life stage) and an additional information module (module D: Benefits and loads beyond the system boundary, as well as stating the methodological provisions relative to the modules. The standards bring transparency to issues of life cycle inventory (LCI), system boundaries, division into the subcategories to be included and so forth. In addition, EN 16485 (2014) developed by CEN/TC175, provides detailed assessment rules for wood and wood-based products for use in construction in line with EN 15804. The international reference life cycle data system (ILCD) handbook (EC-JRC-IES 2010) provides technical guidance for detailed LCA studies that is in line with the international LCA standards ISO 14040 (2006) and ISO 14044 (2006). This was aimed at assuring the quality and consistency of life cycle data, methods and assessments.

The European research project “EeBGuide” (Wittstock et al. 2012) summarized the provisions of CEN/TC 350 and the ILCD handbook in order to produce expert guidance on conducting LCA studies for energy efficient buildings and building products. The aim of the project was not to develop new provisions for LCA, but to provide a common methodology supporting reliable and comparable building and product assessments. The EeBGuide document identified more than 150 topics to be considered for product or building LCAs according to the LCA framework (e.g. goal and scope definition, inventory analysis) and the life cycle stages of the EN 15804 and EN 15978 standards (modules A–D). The provisions and guidance are broken down according to the study types (screening, simplified and complete LCA) and make a distinction between stand-alone LCAs and comparative assertions. Additionally, reporting and review templates for studies are also provided. The guidance document should be helpful in bridging the gap between the standards and practices for building LCAs by consistently merging relevant provisions from CEN/TC 350 and ILCD.

Moncaster and Symons (2013) introduced a simple assessment tool for embodied carbon and energy for UK buildings (the ECEB tool). This tool was developed to help in making design decisions at the feasibility stage by following the EN 15804 and EN 15978 standards as far as possible. The authors demonstrated the use of the tool using a case study building and discussed the methodological discord between the tool and the standards. They concluded that the standards provide accurate analysis for the early life cycle phases (module A1–5) but only an approximation for the latter phases (modules B3–5 and C). It was mentioned that the assessment method given by the standard would not be relevant in early stage calculations for decision making due to a lack of information, leading to uncertainties in the calculation. In addition, the authors mentioned that a lack of proper LCA data, especially for the product stage (module A1–3), the construction process (module A5) and the end-of-life stage (module C), limits the conduct of a proper assessment.

This study demonstrates the use of LCA on a case study wooden building according to the latest normative standards EN 15804, EN 15978 and EN 16485. At first, the assessment was carried out by following the standards and the application of these was studied. Then issues involved in the standards, especially concerning wood products and wood construction, and proposals for further development are discussed from a practical perspective.

2 Methodology

2.1 Scope and data

In order to review the standards, this paper considered only global warming potential (GWP) as an indicator describing environmental impacts and primary energy balance as an indicator describing resource input over the service life of the case study building. The life cycle modules studied and the building parts are summarized in Figure 2. Some life cycle stages and building parts were excluded from the study due to a lack of information. Detailed system boundary and assessment methodologies for each life cycle module are given in section 2.3.

For the building assessment, EN 15978 refers to use data obtained from Environmental Product Declarations (EPDs) defined in EN 15804. However, the authors noticed that there is insufficient open access EPDs for building LCA at present. At the time the research was carried out, only a few datasets (Rüter and Diederichs 2012; IBU 2013) exist that are compiled in line with EN 15804 and include all the detailed subcategories. Therefore, this study was carried out with the ecoinvent database V2.0 (Ecoinvent Centre 2010), which is a widely used generic life cycle inventory (LCI) database and incompatibilities within the data currently used and the requirements in the standard were also observed. GWP was calculated with the CML 2001 method (Frischknecht et al. 2007a) from the LCI data in ecoinvent.

2.2 Case study building

The building studied was a 4-story apartment block located in Mietraching (Architect: Schankula Architekten/ Diplomingenieure, Structural engineers: Bauart Konstruktions GmbH + Co.KG, Constructor: Huber&Sohn Co.KG), approx. 50 km south-east of Munich and completed in 2010. Key information about the building is summarized in Table 1, whilst Figure 3 shows the basic floor plan, section and appearance of the building. The functional unit used in this study was one m^2 of living floor area, which is an area within the inside of the walls, excluding technical spaces and maintenance spaces (e.g. machine room and storage space). Because of the aims of this study, the definition of the functional unit does not have any significant influence on the results in this case.

2.2.1 Foundation and floors

The basement is made of a reinforced concrete structure. The ground floor consists of three layers on top of the basement: rock wool insulation, cement screed and parquet flooring. The intermediate floor consists of five layers: glulam panel, gravel fixed by latex, mineral wool, cement screed, and parquet flooring. The glulam panel slab was prefabricated in a factory and the other layers were installed on site.

2.2.2 Exterior wall

The exterior wall consists of eight layers: larch cladding, battens, wind barrier sheet, rock wool insulation, vapour barrier sheet, gypsum board, massive timber panel, which is literally a mass of sawn timber laid side-by-side and nailed to a laminated veneer lumber (LVL) frame, and two sheets of gypsum board. The U-value is 0.15 W/m^{2}K. The exterior wall element was prefabricated including windows and doors, and assembled on the construction site.

2.2.3 Roof

The roof element is composed of six layers: gravel, glass fleece, waterproof PVC sheet, particleboard, LVL, rock wool, wood batten and plywood. The U-value is 0.14 W/m^{2}K. All layers above the PVC sheet and ceiling board (plywood) were installed on the site.

2.2.4 Other elements

The balcony, composed of LVL panels, a steel staircase and an elevator shaft made of cross-laminated timber (CLT) panel with larch cladding, was also prefabricated in the factory and installed on the site. The building site was paved with grass. The internal walls were fabricated as light-weight, dry-wall construction with gypsum board panels on steel studs and rock wool insulation inside the cavities.

2.3 Boundaries and calculation of impacts at each life cycle stage

2.3.1 Module A1–3: Product stage

The product stage of a building, the so called “cradle-to-gate” process, assesses the environmental impacts from the manufacturing process of all components in the reference building. The impacts were calculated by multiplying the mass of each building component (kg) and unit impact value (MJ/kg or kg CO_2e/kg) obtained from the database. The inventory was carried out from the architect’s and structural engineer’s working drawings. The calculated mass of each component was cross-checked with the material order list provided by the constructors. Due to lack of information, building service equipment and furniture were excluded from the inventory, even if they were integrated to the building element. The inventories included are summarized in Table 2.

2.3.2 Module A4–5: Construction process stage

All information regarding the construction stage was collected by reviewing the construction documents and interviewing the constructors. The transportation of building components and elements was modelled according to the case. The impact from the transportation process was calculated by multiplying the distance (km) and the mass of deliverable (ton), taking the vehicle type into account. Worker transport to the factory or construction site was not included.

Energy consumption during the prefabrication of the wood-based building elements in the factory was monitored by electricity meters. For the prefabrication process, the inventory included electricity for the production line (e.g. operation of machinery, lighting and ventilation systems), space heating energy and fuel for construction machinery. Energy consumption during on-site construction, from ground work to the assembly of the prefabricated elements, was estimated based on information obtained from interviews. For on-site work, the inventory included electricity for the operation of the construction infrastructure and equipment, and fuel for construction machinery. Where only aggregated data (e.g. monthly diesel consumption) was available, allocation was applied on a physical basis (e.g. production volume of each section in the factory). The prefabrication and installation of the steel staircase and building services, and temporary construction work and devices (e.g. scaffolding) were excluded from the calculation due to lack of information.

Waste management methods and transportation to waste treatment facilities were modelled based on information obtained from interviews. Wood process waste was counted as a recycled energy resource for the prefabrication factory. Plastic and steel wastes were assumed to be recycled as secondary materials. It was assumed that gypsum waste was fully landfilled and mineral waste was considered to be incinerated without any energy recovery. Material losses during transportation were not included in the model due to lack of information. The amount of waste from prefabrication and on-site construction work were assessed based on the constructor’s data and literature (Perifoy and Oberlender 2002; Holm et al. 2005; Popescu et al. 2005; Bröklund and Tillman 1997).

2.3.3 Module B: Use stage

The use stage covers the period from the completion of the construction work to the point in time when the deconstruction of the building starts. The reference service period of the case study building was set at 50 years in this study. Module B consists of seven sub-modules: Use (B1, Emissions of dangerous substances to indoor air during the use stage), Maintenance (B2), Repair (B3), Replacement (B4), Refurbishment (B5), Operational energy use (B6) and Operational water use (B7). In this paper only sub-modules B2–6 were considered due to the nature of the study objective and a lack of information.

Repair, replacement and refurbishment work were modeled according to the expected service life of the building components listed in Table 2. Repainting of the exterior cladding (four times) were taken into account in module B2 and replacement of windows, plastic products and rubber products were counted once in B4. It was assumed that all replacement was done with the same materials as originally used and the components replaced were incinerated without any energy recovery. It was assumed that there was no repair or refurbishment work carried out during the reference service period of the building.

The energy demand for the operation of the building was calculated on the basis of 31.83 kWh/m^2/a for district heating by radiator and 31.31 kWh/m^2/a for electricity use in the whole building, based on German standard DIN V 4108-6 (2003). According to the general German energy mix, heating energy was assumed to be supplied by a CHP plant, using 42% natural gas, 39% coal, 12% lignite and 7% waste incineration (The German Heat and Power Association 2006). In addition, it was assumed that 70% of electricity was provided by the CHP plant. For the remaining 30% of electricity, the national average supply mix data from the ecoinvent database was used.

2.3.4 Module C: End of Life stage

The end of life (EoL) stage is divided into four sub-modules: deconstruction/demolition (C1), Transport (C2), Waste processing (C3) and Disposal (C4). A framework for moving towards a European recycling society with a high level of resource efficiency has the aim that by the year 2020 at least 70% (by weight) of non-hazardous construction and demolition waste shall be prepared for reuse, recycling or material recovery (OJ L312 2008). In this study the end-of-life scenarios for building components were made according to this approach. EoL options for each material are summarised in Table 2. All EoL processed: deconstruction work, transportation to sorting or disposal, waste sorting and processing, and disposal (incineration or landfilling), were taken into account.

2.3.5 Module D: Benefits and loads beyond the system boundary

The net environmental benefits or loads resulting from reuse and recycle of materials and energy exiting the system boundary can be described in module D as potential resources for future use. Renewable and non-renewable primary energy resources used as raw material (energy content (net caloric value, MJ)) in the building was counted by referring to the ecoinvent database documentation (Frischknecht et al. 2007b). Biogenic carbon storage in the wood products was also counted according to standard EN 16485 and EN 16449 (2014) as a benefit of the system studied, although there is no provision regarding the carbon storage issue in EN 15804 and EN 15978. This point is discussed in section 3.2.4 in detail.

3 Results and discussion

3.1 Results

Figures 4 and 5 show respectively the life cycle GWP and primary energy balance of the case study building according to the provisions set out in the standards. The life cycle modules for which no values were determined have been excluded from the figures. In Fig. 4, the GWP for all the building life cycle stages (modules A to C) are presented. In addition, the temporal biogenic carbon storage in the building materials used is displayed in module B1 as a negative value and carbon storage in recycled and reused materials exiting the system boundary is expressed in module D as positive values, in accordance with EN 16485. Here, in general, greenhouse gas (GHG) emissions from biogenic fuel combustion is regarded as zero emission for the all life cycle modules based on the idea of carbon neutrality. Thus in this case the values for “GHG emissions” indicate only the emission from fossil fuel combustion. However, in order to explain the biogenic carbon balance over the building life cycle, the GHG emissions from the incineration of some of the wood products used in the building for energy production was counted as a positive value in module D (167 $kgCO_2e/m^2$). Biogenic carbon emissions from module A5, incineration of wood process residues for energy production, was included in this value as well. The use stage (module B6) and the product stage (module A1–3) account for about 70% and 20% of the total GWP, respectively. Contributions to the other life cycle stages are very minor. The temporal biogenic carbon storage in module B1 is nearly equal to the sum of GHG emissions from module A1-5. According to the EoL scenario, about 300 $kgCO_2e/m^2$ of biogenic carbon storage is transferred to the next life cycle system.

In Fig. 5, the use of renewable and non-renewable primary energy for all the life cycle modules is displayed separately. The energy content of the building materials used is expressed according to the term defined by the standards; “use of renewable primary energy resources used as raw materials” and “use of non-renewable primary energy resources used as raw materials”, in module A1-3 and B4 as positive (consumption) value. In addition, the energy content in recycled and reused materials exiting the system boundary, as well as energy recovery (exported energy) from the incineration of some of the building components, including wood process residues from module A5, are expressed separately as a negative value in module D. The use stage (module B6) and the product stage (module A1-3) dominate, accounting for about 65% and 25% of the life cycle primary energy consumption respectively. The share between these modules changes when the energy content of the building materials is included as primary energy consumption, resulting in module A accounting for about 35% and module B6 for about 60%.

3.2 Discussion

In the case study, it was demonstrated that EN 15978 could provide the basic pathway for building LCAs. In particular, as Moncaster and Symons (2013) discussed, a detailed analysis can be carried out for the early life cycle stages up to the end of construction process (module A1–5) based on real data, although the assessment of the latter life cycle stages (module B and C) seems to be rather approximate due to the many assumptions made. EN 16485 gives detailed rules for the assessment of wood products in line with EN 15804, specifically focusing on the inherent material properties (e.g. biogenic carbon flow, energy content). The inherent properties of wood products are a sensitive issue and the handling of this aspect has thus far often been disputed (Lippke et al. 2010, Werner and Richter 2007), however EN 16485 seems be able to provide a certain amount of clarity on this issue.

However, it can be said that the standards still include many ambiguous descriptions. The authors encountered some difficulties in the case study because of provisions in the standards. In this section, problematic points found in the standards are discussed in light of the following practical aspects: data for the assessment, system boundary, scenarios and communication of the assessment results.

3.2.1 Data for the assessment

As mentioned before, in this study the assessment was conducted with generic LCA data. Although EN 15978 refers to use EPDs based on EN 15804 for building assessment, such data is clearly lacking at the moment. Moncaster and Symons (2013) also mentioned that the main difficulty in conducting a proper assessment is the lack of LCA data. Moreover, it is mentioned in EN 15978 that if no specific or representative EPD in accordance with the requirement of EN 15804 is available, generic EPD or data set of a similar product may be used and adapted to create a new data set to reflect the actual situation as closely as possible, in the assessment of the product stage (module A1-3). Firstly, generic EPDs or similar data set would be relevant in the beginning of design phase rather than specific EPDs, since specific product would not be decided at that phase, in general. Secondly, there is some discord between the methodology used in ecoinvent and the provisions laid out in EN 15804. For instance, the standard regulates to show the use of primary energy and use of primary energy resources used as raw material (energy content) separately as the energy input. However, at the moment it is not possible to distinguish these values in the ecoinvent database. As described in the EeBGuide (Wittstock et al. 2012), in many cases it is not easy for users to modify or adapt existing generic LCA data. The preparation of a sufficient number of data of suitable format and quality is thus urgently required, especially for the assessment of data-intensive modules such as the product stage (module A1–3), construction process (module A5) and end-of life stage (module C). The manufacturing and construction industries are expected to develop data according to EPD format described in EN 15804.

3.2.2 System boundary

The life cycle stages defined by EN 15978, in general, seem to be reasonable. However, one problematic point was found. In principle, the construction stage (module A4–5) covers the processes from the factory gate of the construction products to the completion of the on-site construction work. This means that the environmental impacts and aspects linked to the prefabrication process of the building elements (e.g. exterior wall element) and their transportation are accounted for in the product stage (module A1–3). But in reality the prefabrication work is often practiced in a factory other than the where the product in manufactured. In addition, sometimes the same constructor carries out both off-site prefabrication and on-site construction work. In such situations, the environmental impacts would be unfairly allocated to module A1–3 and a proper interpretation of the assessment result would become rather difficult. In this study, therefore, the prefabrication process was accounted for in module A4–5 as a part of the construction process and module A1–3 was purely expressed by the environmental impacts related to the manufacturing processes of the building materials. In order to make a distinction between the prefabrication process and on-site construction process, additional life cycle modules in the construction process stage (e.g. module “A4–5: P” for prefabrication process, module “A4-5: O” for on-site construction process) are to be recommended.

3.2.3 Scenarios

The standards provide the rules for setting the appropriate scenarios representing the assumptions made in the assessment; however some difficulties in following the rules were encountered. For instance, the construction involves many sub-constructors and several construction works may, in general, be progressing at the same time. Thus it is rather difficult to follow all the processes going on in detail, especially during the on-site construction work. Simplification of the assessment for the construction process stage would be required by, for instance, reducing the number of processes needing to be covered, or preparing a reference data based a sufficient number of case studies as guided in EeBGuide (Wittstock et al. 2012).

3.2.4 Communication of the assessment results

Proper communication of the assessment results seems to be challenging issue. Simplification of the information would make the content more understandable. But on the other hand, it might cause the results to be misread. In particular, the information in module D should be treated carefully.

Linking biogenic carbon flow with the idea of carbon neutrality in LCA is a complex issue and there is as yet no common reporting rule for biogenic carbon storage value. As described previously, EN 15804 and EN 15978 do not provide any provisions regarding biogenic carbon storage. However, it is mentioned in EN 16485 that the carbon storage in the building products used for a specific time shall be reported in module B1 as a negative value and biogenic carbon content exiting the system boundary from module C3: biogenic carbon emission arising from the incineration of wood products for energy production and the carbon storage in recycled/reused materials, in module D, as a positive value. On the other hand, for instance, German EPDs (IBU 2013) count the carbon storage in module A1 as an input (negative value) to the system studied and displayed as an aggregate along with the GHG emission from module A1-3.

In Fig. 4, biogenic carbon flow was reported according to the provisions in EN 16485; however this raises some points for discussion. For instance, when biogenic carbon storage is described in module B1 it should represent the amount of carbon stored in the wood products actually assembled into the building (net amount, -428 $kgCO_2e/m^2$), whilst the value described in module D (167 $kgCO_2e/m^2$) is an aggregate of biogenic carbon emission from the incineration of wood process residues produced in module A5 (33 $kgCO_2e/m^2$) and also the incineration of wood products exiting the system boundary from module C3 (134 $kgCO_2e/m^2$), as explained previously. As consequence, the values in module B1 and module D do not give a zero balance, due to a lack of information regarding the wood process residues from module A5 (33 $kgCO_2e/m^2$) in the value of module B1.

This gap might make the result difficult to understand. In this sense, it seems relevant to count the temporal biogenic carbon storage in the building materials on the basis of the gross amount (-461 $kgCO_2e/m^2$, including materials lost in latter modules) in module A1 as an input to the system studied and to describe biogenic carbon emission arising from the exported energy clearly according to the life cycle modules where it happens. In addition, biogenic carbon storage in recycled/reused materials could be expressed as negative values as an environmental benefit of the system studied. Counting such carbon storage as a positive value and making biogenic carbon flow zero in the system would make sense for the purpose of avoiding double counting. In this way, however, the environmental benefit of the system would not be explained properly. Both temporal carbon storage in the building materials for the expected service life and in recycled/reused materials for next system should be described as a benefit of the system, since, at least it is clear benefit to delay emitting CO_2 for a certain period by storing the carbon in building products.

In many cases, the energy content of the building components are accounted for in module A1–3 as a part of the embodied energy. As described previously, EN 15804 and EN 15978 regulate the reporting of the use of primary energy for energetic purpose and the use of primary energy resources for the raw materials (energy content) all should be shown separately as resource input (consumption). This definition could be discussed for further developing the communication system of building LCA. In the case of sawn timber, for instance, the energy content is equivalent to the solar energy used by the tree for its growth. If this energy content is taken into account as energy consumption in a product or building system solar energy, converted into electricity or heating via a photovoltaic panel or thermal collector integrated into a building, should be counted as energy consumption in module B6 as well. Thus it would be important to draw the system boundary clearly between natural phenomena and human activities. From this aspect, it would be rather reasonable to regard such energy content as the potential for the energy recovery at the end of life of the materials, which can be utilized in the next system. At the same time, the energy content naturally needs to be counted as energy consumption if building materials with energy content are wasted without producing any energy, according to the scenarios. In other word, energy content should be counted as a benefit when it is utilized as an energy resource properly and vice versa.

3.2.5 Examples of developed presentation of the assessment results

Based on Figure 4 and 5, examples of a communication system developed according to the discussions in section 3.2.2 and 3.2.4 for the life cycle GWP and primary energy balance are shown in Figure 6 and 7. Firstly, it would be more understandable to express the information in module D within modules A-C, rather than as an individual module after module C. In this way, module D would be explained more accurately and misunderstanding of the information due to aggregated value in the module would be avoided. In addition, a distinction between the prefabrication process and the on-site construction process was made as A4-5: P (prefabrication) and A4-5: O (On-site). A4-5: P includes the transportation of building materials from the product's factory to the prefabrication factory and all prefabrication process conducted in the factory. A4-5: O includes the transportation of building materials from the product factory to the construction site, the transportation of the prefabricated building elements from the prefabrication factory to the construction site and all on-site construction process.

In Fig. 6, temporal biogenic carbon storage is expressed in module A1-3 (-461 $kgCO_2e/m^2$) and the storage in recycled/reused materials in module C (-294 $kgCO_2e/m^2$, as the information under module D), whilst biogenic carbon emission from wood process residues and wood products are described in module A4-5: P (33 $kgCO_2e/m^2$) and C (134 $kgCO_2e/m^2$) as the information under module D. Here biogenic carbon flow in the system studied has a zero balance. In Fig.7, energy content is counted as a positive value under the category of "use of renewable primary energy resources used as raw materials" and "use of non-renewable primary energy resources used as raw materials" in module B4 and C, where wood, plastic and rubber products are assumed to be wasted with no energy recovery. Otherwise, energy content is counted as a benefit of the system.

The communication system demonstrated in Figs. 6 and 7 is a possible example. In this way, the scenario with higher recycle/reuse ratio evidently becomes preferable. This system could show the environmental benefit of recyclable materials (not only steel but also wood and plastic etc. too) more clearly, and would help stimulate recycle/reuse -consciousness in society in line with EU strategy (OJ L3 12 2008).

4 Conclusions

In this study, the global warming potential and the primary energy balance of a wooden reference building were assessed over its life cycle according to the method described in the latest standards: EN 15804, EN 15978 and EN 16485. The assessment was carried out by following the standards and discord between the standards and the assessment practice in reality is discussed. In principle, it can be concluded that the standards provide basic guidelines for the building assessment, although they still cannot lead to fully comparable results because of, for instance, freedom in the definition of system boundary, scenario and so forth.

Some difficulties were also found in conducting the assessment in compliance with the standards. A lack of data for the assessment is a critical issue. Nowadays, many LCI or life cycle impact assessment (LCIA) data are available for the building assessment all over the world. However, most of these databases have been developed for a specific purpose and scope and are as yet not been in line with the standards (Takano et al. 2014). LCA is a data-intensive method so that the preparation of a proper database for building assessment is certainly required.

This paper also raised the question about the life cycle modules defined by EN 15804 and EN 15978. In the current standards, the prefabrication process is classified within the product stage (module A1–3). But in many cases, prefabrication of the building elements is practiced in a factory other than the factory manufacturing the building product. In some cases, the same constructor is simultaneously managing both off-site and on-site construction work and in this context, this paper suggests an additional life cycle module for the prefabrication process in the construction process stage (module A4–5). In addition, simplification of the assessment for the construction stage would be relevant because of the complexity of the process. Further study could be required to understand which unit process really needs to be covered in the assessment and also to set reference data based on a sufficient number of samples.

The system of communicating the assessment results could also be developed. In particular, the information in module D showing the environmental benefits or loads beyond the system boundary should be expressed carefully. For instance, wood products incorporate biogenic carbon storage and energy content, which are inherent properties that other common construction materials, such as concrete and steel, do not have. Possible examples of the presentation of the assessment results were shown and discussed. Showing such a product’s potential in an inappropriate way may result in the building assessment results being misread. The environmental impacts and aspects of the system studied, of course, should be displayed fairly and in common manner. Moreover, it would be of importance to develop the communication system in such a way as to stimulate the environmental -conscious in society. In order to develop a relevant communication system, further discussion and case studies would be important and feedback from such practices should be incorporated into the development of the guideline for the assessment.

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Tables

Table 1 Key information about the case study building

Use	Location	Structure frame	Gross area (m^2)	Living area (m^2)	Floors	Operative energy use ($kWh/m^2/a$)*
Residential	Germany	Sawn timber panel	726	488	5	63

*Operative energy use is the secondary energy including electricity and heating energy

Table 2 Mass, expected service life and end-of-life options of materials used in the case study building

Material	mass (kg)	Expected service life (year)	End-of-Life scenario			
			reuse (%)	recycling (%)	incineration (%)	landfill (%)
Sawn timber (soft wood)	53048	50	20	50	30	
Sawn timber (hard wood)	10561	50		30	70	
LVL	6937	50	20	50	30	
Glulam	37577	50	20	50	30	
CLT	8864	50	50	20	30	
Particleboard	2474	50			100	
OSB	1248	50		70	30	
Plywood	865	50		70	30	
Wooden window frame	810	30			100	
Concrete	329762	50		100		
Cement	66603	50		20		80
Mortar	2224	50		20		80
Gravel	67314	50	100			
Plaster	584	50				100
Reinforcement steel bar	10480	50	100			
Steel products	21401	50		90		10
Aluminium products	99	50		90		10
Gypsum board	36766	50		20		80
Triple glazing	2778	30		50		50
Rock wool	8087	50				100
Glass fleece	108	50				100
Plastic products	768	35			90	10
Rubber products	285	35			90	10
Waterborne paint	392	10			90	10
Sheet material (water proof etc.)	564	50			90	10
Glue	330	50				100
Latex	489	50				100
Grass	2000	50				

Figure captions

Fig. 1 Life cycle modules for building LCAs according to EN 15978 standard.

Fig. 2 Included life cycle modules and building parts

Fig. 3 Basic floor plan, section and appearance of the case study building

Fig. 4 Global warming potential of the reference building described in accordance with provisions in the standards

Fig. 5 Primary energy balance of the reference building described in accordance with provisions in the standards

Fig. 6 Global warming potential of the reference building described in accordance with the discussions in section 3.2.2 and 3.2.4

Fig. 7 Primary energy balance of the reference building described in accordance with the discussions in section 3.2.2 and 3.2.4

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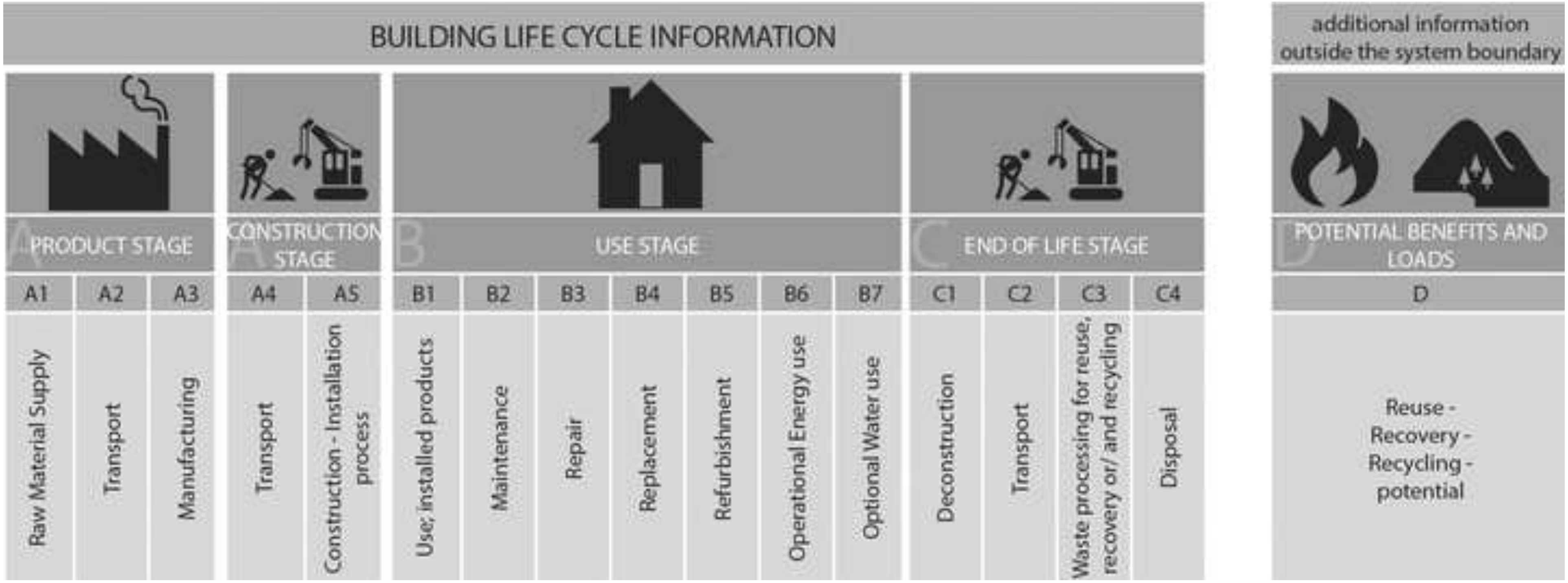


BUILDING LIFE CYCLE INFORMATION																additional information outside the system boundary
PRODUCT STAGE			CONSTRUCTION STAGE		USE STAGE							END OF LIFE STAGE				POTENTIAL BENEFITS AND LOADS
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw Material Supply	Transport	Manufacturing	Transport	Construction - Installation process	Use; installed products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy use	Optional Water use	Deconstruction	Transport	Waste processing for reuse, recovery or/ and recycling	Disposal	Reuse - Recovery - Recycling - potential

BOUNDARIES AND SCENARIOS

Covered life cycle modules

- ■ Assessed
- ▨ Partly assessed
- □ Not assessed

- ■ Production stage module A1-3
- ■ Construction stage module A4-5
- ▨ Use stage module B
- ■ End-of-life stage module C
- ■ Additional information module D

Note

In module B, Maintenance (B2), Replacement (B4) and Operational energy use (B6) were taken into account.

SYSTEM BOUNDARIES REGARDING BUILDING PARTS

Building parts included in the study

- ■ Assessed
- ▨ Partly assessed
- □ Not assessed

Element

- ■ Basement
- ■ Ext. Wall
- ■ Int. Wall
- ■ Floor
- ■ Roof
- ■ Stair - EV

Finishes

- ▨ Interior surfaces
- ■ Window / Door
- □ Furniture

External

- ■ Balcony
- ■ Site
- □ Vegetation
- ■ Terraces
- □ Fences
- ■ Pavings

Building services

- ▨ Heating system
- □ Cooling system
- ▨ Ventilation system
- □ Water system
- □ Sewage system
- ▨ Electrical system
- □ Data system
- □ White goods

Temporary

- □ Scaffolding
- □ Temporary cabins
- □ Temporary machinery
- □ Temporary infrastructure
- □ Temporary landfills

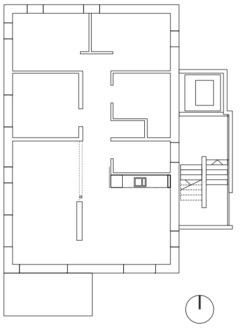
Other

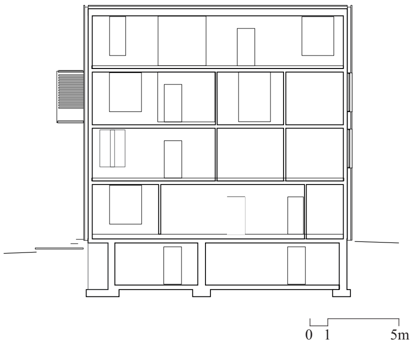
- □ (specify)

Note

Finishes for interior surface of wall were not included.

Embodied energy and emission for building services were not assessed.

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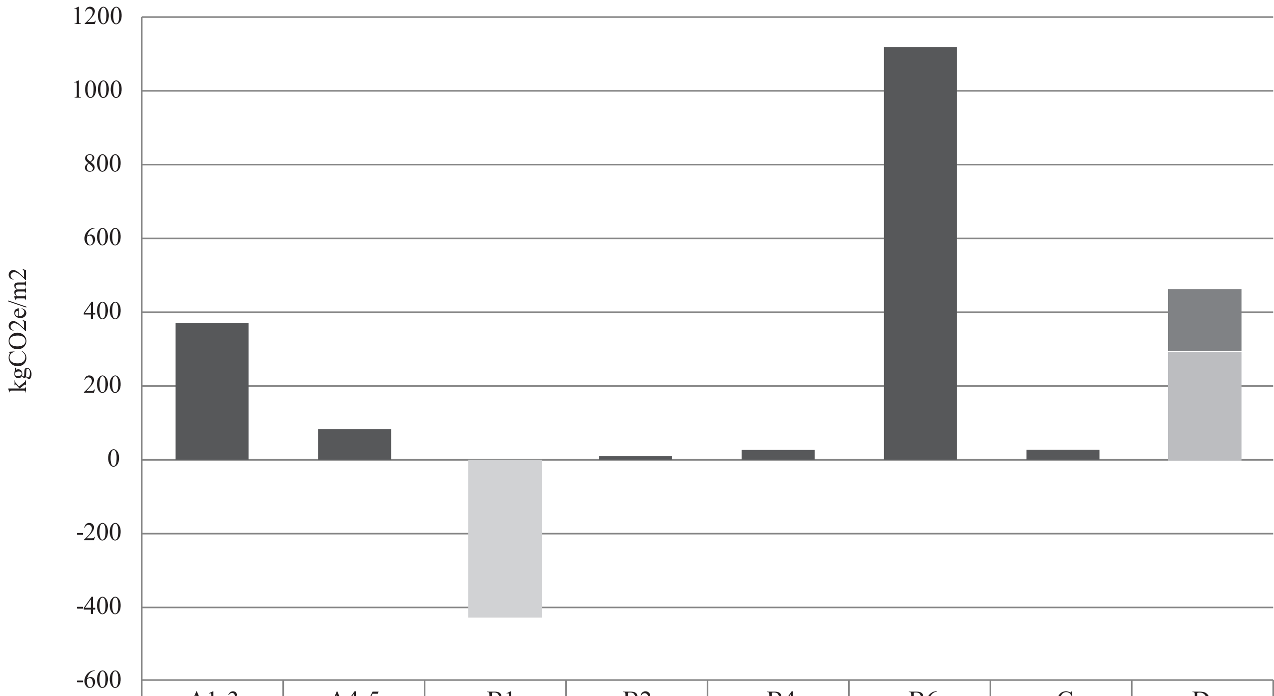
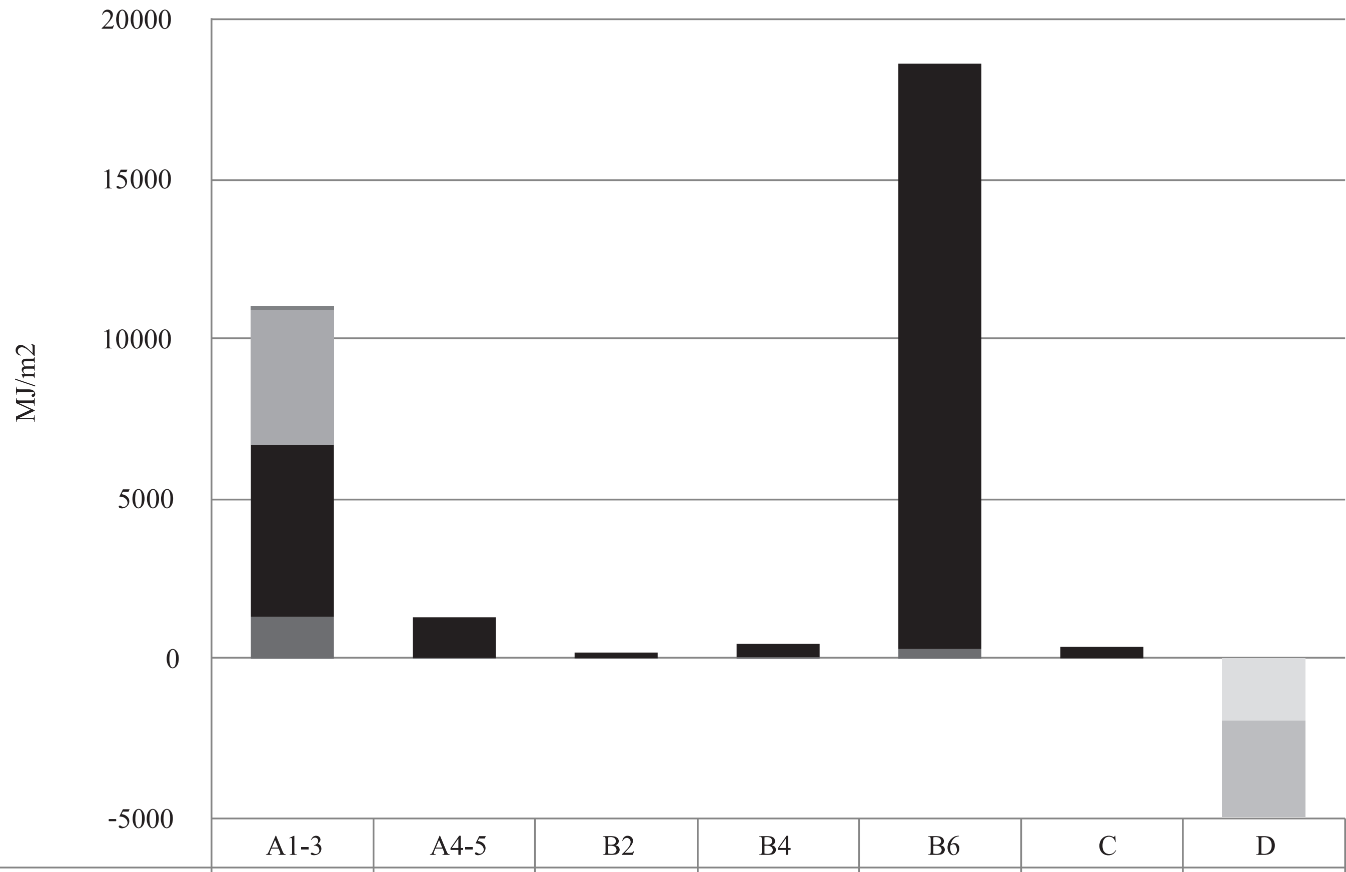
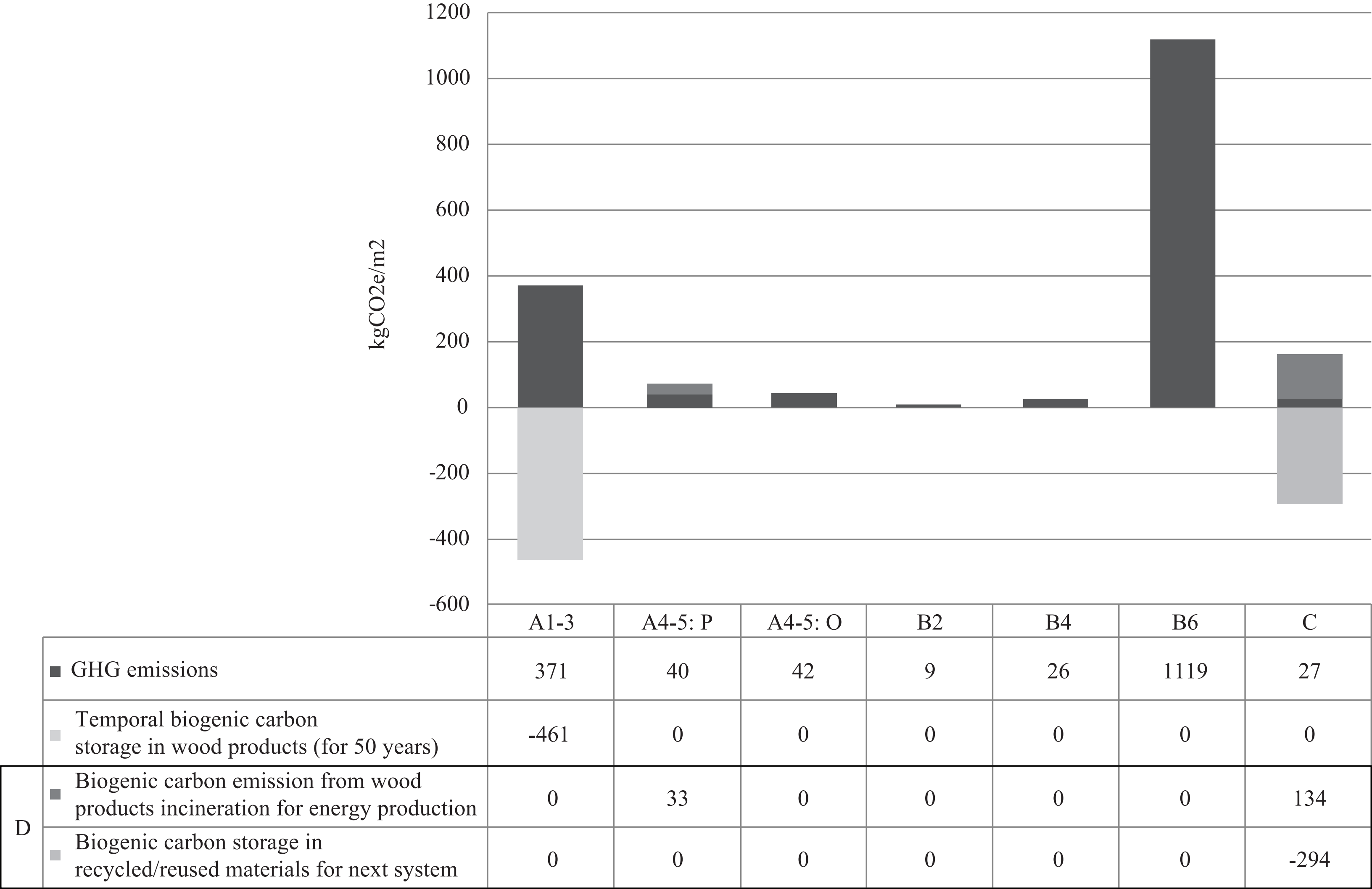


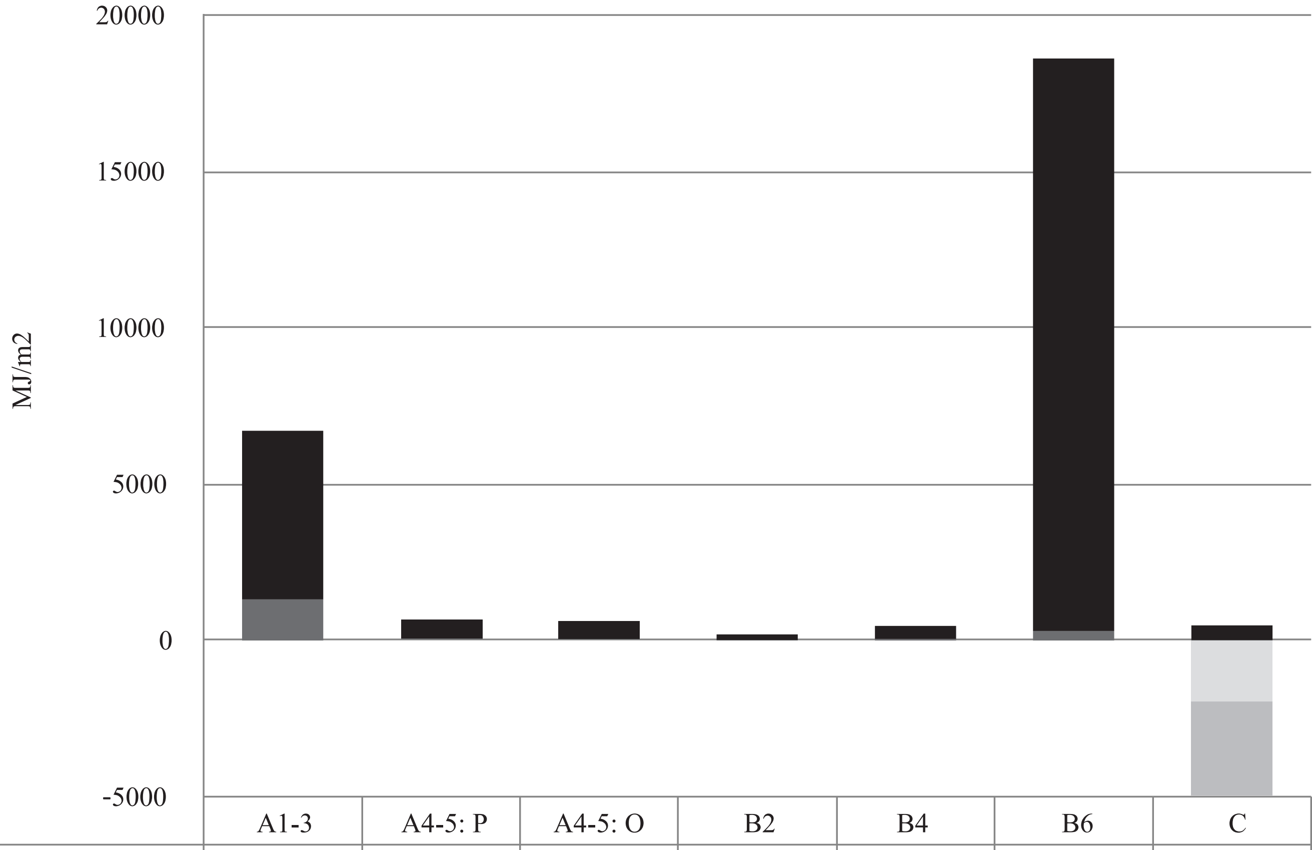
	A1-3	A4-5	B1	B2	B4	B6	C	D
■ GHG emissions	371	82	0	9	26	1119	27	0
■ Temporal biogenic carbon storage in wood products(for 50 years)	0	0	-428	0	0	0	0	0
■ Biogenic carbon emission from wood products incineration for energy production	0	0	0	0	0	0	0	167
■ Biogenic carbon storage in recycled/reused materials for next system	0	0	0	0	0	0	0	294



	A1-3	A4-5	B2	B4	B6	C	D
■ Primary energy consumption Renewable	1311	20	13	49	301	9	0
■ Primary energy consumption Non-renewable	5394	1274	175	413	18306	357	0
■ Use of renewable primary energy resources used as raw materials	4541	0	0	87	0	0	0
■ Use of non- renewable primary energy resources used as raw materials	66	0	0	45	0	0	0
□ Exported energy for next system	0	0	0	0	0	0	-1846
■ Energy content in recycled/reused materials	0	0	0	0	0	0	-2742



		A1-3	A4-5: P	A4-5: O	B2	B4	B6	C
	■ GHG emissions	371	40	42	9	26	1119	27
	□ Temporal biogenic carbon storage in wood products (for 50 years)	-461	0	0	0	0	0	0
D	■ Biogenic carbon emission from wood products incineration for energy production	0	33	0	0	0	0	134
	□ Biogenic carbon storage in recycled/reused materials for next system	0	0	0	0	0	0	-294



		A1-3	A4-5: P	A4-5: O	B2	B4	B6	C
	■ Primary energy consumption Renewable	1311	15	5	13	49	301	9
	■ Primary energy consumption Non-renewable	5394	655	619	175	413	18306	357
	■ Use of renewable primary energy resources used as raw materials	0	0	0	0	87	0	0
	■ Use of non- renewable primary energy resources used as raw materials	0	0	0	0	45	0	18
D	■ Exported energy for next system	0	-336	0	0	0	0	-1511
	■ Energy content in recycled/reused materials	0	-12	0	0	0	0	-2730