Eur. J. Wood Prod. (2018) 76:711–729
DOI 10.1007/s00107-017-1236-1

ORIGINAL

Life cycle assessment of product- and construction stage of prefabricated timber houses: a sector representative approach for Germany according to EN 15804, EN 15978 and EN 16485

Hermann Achenbach[1] · **Jan L. Wenker**[1] · **Sebastian Rüter**[1]

Received: 22 October 2016 / Published online: 17 October 2017

Abstract Energy savings in the use phase of a building's life cycle increased the relative importance of environmental impacts of the product-, construction- and end-of-life stages of a building. The European Committee for Standardization (CEN) thus developed horizontal standards to enable the sustainability assessment of construction works over their entire life cycle. Consistent with the European standards EN 15804, EN 15978 and EN 16485, a life cycle assessment (LCA) was carried out to determine the environmental impacts of the production and construction stages of an average prefabricated timber house produced in Germany as well as its particular building elements (1 m² inner/outer wall, 1 m² roof element, 1 m² ceiling element). The life cycle inventories (LCIs) were compiled on the basis of annual data of 12 participating manufacturers of prefabricated timber houses. A specific LCA model was developed for the calculation of the input- and output flows referring to the functional units on factory level. Furthermore, one focus was laid on the application of the modular principle according to EN 15804/15978 to construction systems with a high level of prefabrication. The normalization to the overall German impacts shows that the contributions to the environmental categories global warming potential (GWP), acidification (AP) and to the abiotic depletion potential (ADPe) are most important. The highest impacts originate from the manufacturing of the building materials. However, for the categories GWP and AP, around 30% of the impacts originate from the prefabrication of the building elements, their transport and the processes at the construction site.

1 Introduction

1.1 Normative framework

Since the European Committee for Standardization (CEN) got a mandate from the European Commission in 2004, its Technical Committee 350 developed a set of horizontal standards which enables the sustainability assessment of construction works. This series of standards contains framework documents (EN 15643− 1 to 4) for the assessment of ecological, economic, socio-functional and technical aspects of a building along its entire life cycle (CEN 2010, 2011a, 2012a, b).

For the specific purpose of communicating the details from particular building product level to building level, the standard EN 15804: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products (CEN 2013) was developed. This is a document for the creation of so called product category rules (PCR) which defines the minimum requirements for type III environmental declarations according to ISO 14025 (ISO 2006a), in particular for building products. The development of harmonized category rules has been an essential task to enable a consistent LCA of different building product types based on ISO 14040/44 (2006b, c) for the use in environmental product declarations (EPDs).

On building-level, EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method (CEN 2011b) regulates the environmental assessment of the whole life cycle of a building. According to the standard, information on the environmental performance of the product stage (cradle to gate) of a building is to be derived from EPDs or other LCA data sets which are in line with EN 15804. EN 15804 and EN 15978

✉ Hermann Achenbach
h_achenbach@posteo.de

[1] Thünen Institute of Wood Research, Leuschnerstrasse 91c, 21031 Hamburg, Germany

are based on the same modular concept (Fig. 1). Hence, for the assessment of the product stage on building level, LCA data on particular building products can simply be summarized within the single modules raw material supply, transport and manufacturing (modules A1–A3).

This set of standards also forms the methodical basis for the German Assessment System for Sustainable Building (BNB) which was developed by the Federal Ministry of Transport, Building and Urban Development in collaboration with the German Sustainable Building Council (DGNB e.V.)

To further clarify the use of the general core product category rules specifically for wooden building products, EN 16485—Round and sawn timber—Environmental Product Declarations—Product category rules for wood and wood-based products for use in construction—was developed within TC 175 (CEN 2014) with complementing specific rules on the basis of EN 15804. EN 16485 contains a description on how to account the wood inherent carbon that is transferred and released to/from the product system with its defined life cycle modules.

1.2 LCAs of timber houses

Numerous studies on life cycle assessment of timber houses according to ISO 14040/44 have been carried out (e.g. Gustavsson et al. 2010). Many of them compared the environmental impacts of wood constructions and buildings from other materials, such as concrete, bricks and steel (e.g. Peuportier 2001; Scharai-Rad and Welling 2002; Guardigli et al. 2011; Monteiro and Freire 2012). However, due to the lack of specific rules for LCAs of building products and whole buildings, which have been provided by the release of the above mentioned standards, these studies vary widely with respect to their methodical approaches and, as a consequence, in the results and their interpretation.

Following the standard EN 15978, König and de Cristofaro (2012) conducted LCAs for typical residential buildings with several housing units. In the context of the German sustainability-assessment schemes BNB and DGNB, they published a benchmarking study. For each type of building they assessed the environmental impacts from different types of materials and construction methods. In the case of wood, they selected a wood-frame-construction and a massive-timber-construction. The assessment was done for the product stage (modules A1–A3), the use stage including modules B2-B4 and B6 as well as the end-of-life stage (modules C and D). However, processes in the prefabrication of wooden wall-, ceiling- and roof elements, which belong to the product stage, were not taken into account. Modules A4 (transport to the construction site) and A5 (construction site) (see Fig. 1) were also not considered, and LCA data of wooden building products that have been calculated in line with the requirements of that standard (cf. Rüter and Diederichs 2012), could also not be used.

A four-storied light weight wooden building near Växjö (Sweden) was studied by Peñaloza et al. (2013). For the LCA of different construction systems in line with EN 15978, the building was redesigned in three different ways. Beside systems from cross laminated timber and beam columns which

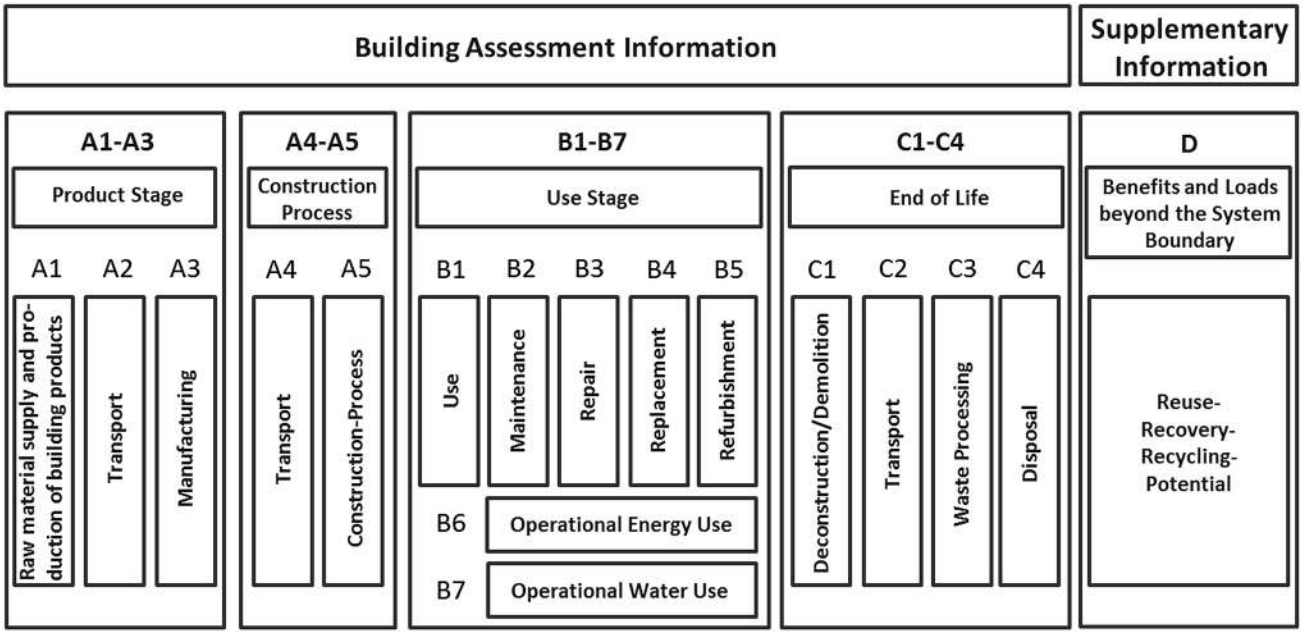


Fig. 1 System boundaries according to EN 15804/EN 15978

are built on construction site, a construction of prefabricated volumetric modules was assessed over its entire life cycle (modules A1–A3, A4–A5, B1–B5, C1–C4). In the case of the volumetric modules, also the transport module A4 was additionally taken into account by a sensitivity analysis with a distance of 1306 km and a total weight of 268 tons. Peñaloza et al. (2013) pointed out that the actually required amount of transportation of the building elements should be defined by volume rather than by weight. They identified this issue for potential further research.

Takano et al. (2015) conducted an LCA for the whole life cycle of a four-storied apartment block with a structure built from sawn timber and various engineered wood products by following EN 15804, EN 15978 and EN 16485. They interviewed the constructors for assessing the prefabrication of the building elements, their transport to the construction site as well as the construction processes onsite. According to EN 15978, the construction stage (modules A4–5) covers processes beyond the factory gate while prefabrication in the factory has to be accounted for in module A3. However, Takano et al. (2015) mentioned that this provision firstly may lead to a misinterpretation of the assessment results, because it would make the comparison of the mandatory EPD modules A1-3 difficult. Secondly, the authors pointed out that the results for module A1–3 may be distorted in favor of an onsite construction system. Therefore, Takano et al. (2015) divided the modules A4–5 in A4-5: P (P stands for prefabrication) and A4–5: O (O stands for onsite).

1.3 Aim of the study

Due to the progressive increase of energy savings in the use phase of buildings, the environmental impacts of the product and construction stages are gaining more and more importance. For this reason, the main goal of this study is to provide representative LCA-data for the product and construction stages (modules A1–A5) of prefabricated single- and double-family timber houses produced in Germany and their particular building elements in line with the standards EN 15804, EN 15978 and EN 16485. Whereas all referred literature in Sect. 1.2 are case studies on specific buildings, the data acquisition for the life cycle inventories within the present study was carried out on the factory sites of 12 participating manufacturers of prefabricated houses. In contrast to Takano et al. (2015), the prefabrication of the building elements was considered within the product stage (modules A1–3). To be in line with EN 15804, it was necessary to calculate the life cycle inventories (LCI) of the functional units based on annual data of each factory site. The main challenge regarding this issue was to develop an LCA model that allocates the annual input- and output flows on factory level to each type of building element (inner/outer wall, ceiling and roof). Considering the proposal of Peñaloza et al. (2013) for further research on the impact of the transport of building elements to construction site, this study also focused on module A4 by collecting annual data. The issue of accounting for the prefabrication process either in the product stage (modules A1–A3) or -as done by Takano et al. (2015) - in the construction stage of the building (A4–A5) is also part of the discussion.

The results of the presented study are also published in the Thünen Report 38 in German language (Achenbach and Rüter 2016).

2 Scope definition and methods

2.1 System boundaries

The study focuses on the production- and the construction process. Therefore, it includes the raw material supply and manufacturing of the integrated semi-finished products (module A1), the transport (A2), the manufacturing of the building elements (A3), the transport to construction site (A4) and the processes at the construction site of the buildings (A5). All semi-finished building products considered by the study can be seen in Table 2. By using the top-down approach based on the allocation of annual input-and output data of the manufacturing process, it was not possible to get data on materials used for the roof tiles, stairs, balconies and technical equipment. The benefits and loads resulting from thermal utilization of the product package are provided as additional information beyond the product life cycle (D). Whereas modules A1 and A2 rely on generic background and scenario dependent data, modules A3–A5 use the data from the actual manufacturing and transportation processes of the building elements and from the construction site. Figure 2 shows an overview of the system boundaries and the life cycle stages considered. Additionally, it provides a detailed insight into the manufacturing process of the building elements, which is represented by primary data collected within module A3.

2.2 Wood inherent carbon balance

Wood which enters the product system from the ecosystem contains biogenic carbon that has been sequestered during the growth of the trees and that has been incorporated as material inherent property of the wood. At the point of raw material extraction, this carbon is equally transferred onto the product system. Parts of the biogenic carbon again leave the product system at the production of semi-finished goods (module A1) and during the manufacturing of the building elements (A3) when wood is burned for energy generation as well as when the wooden building products are burned at the end of their life cycle (C3). In line with the requirements

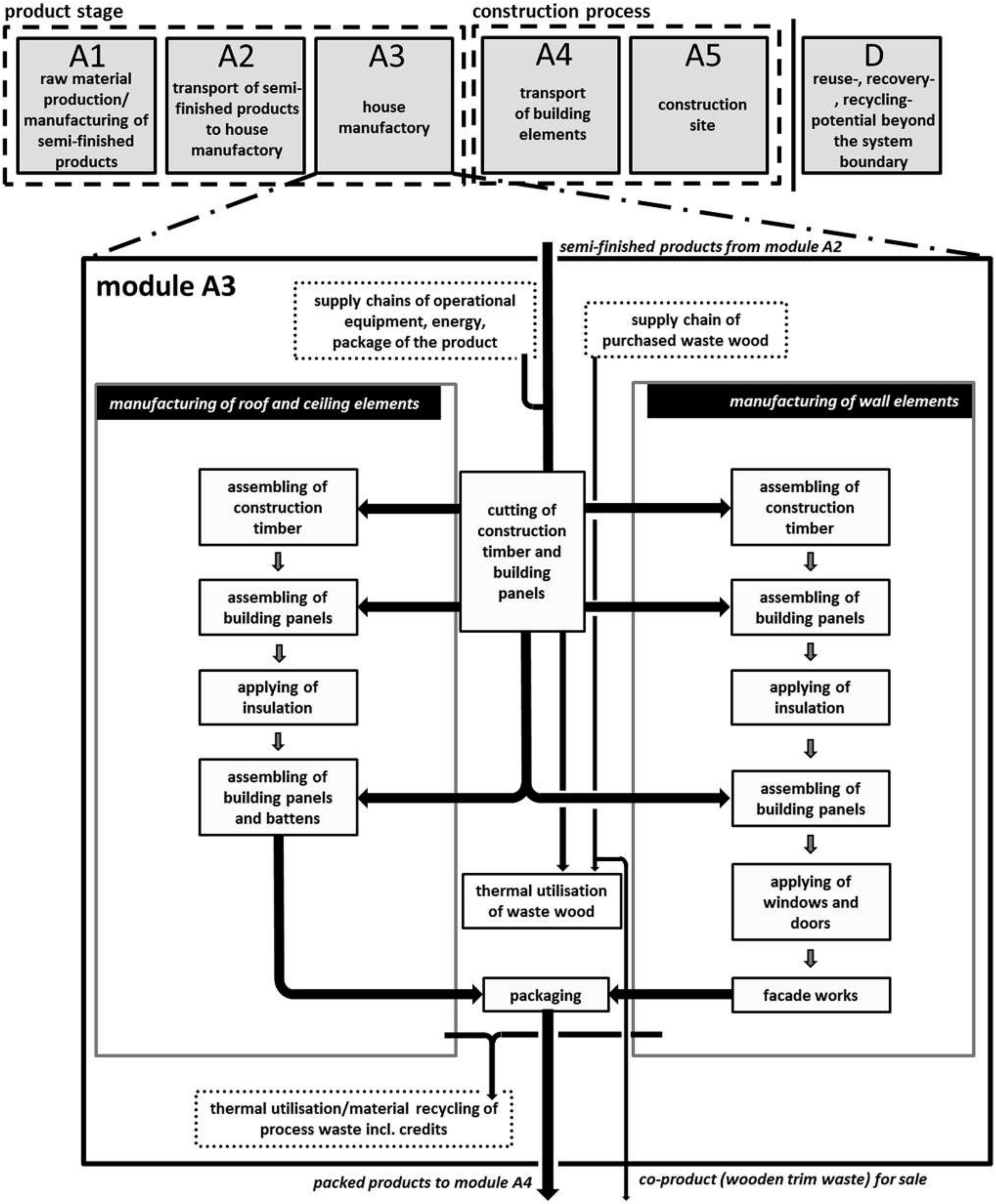


Fig. 2 System boundaries and detailed manufacturing process of the building elements

of EN 15804 (CEN 2013) and EN 16485 (CEN 2014) the carbon balance of the studied system was taken into account as follows (cf. Rüter and Diederichs 2012; Rüter 2013):

In the modules A1 and A3, the transfer of wood inherent carbon onto the product system is considered as input. Within the GWP category, this biogenic carbon content is expressed as CO_2 and counts as negative value (− 1) in the case that wood originates from countries accounting for article 3.4 of the Kyoto Protocol or from forests which are operating under established certification schemes regarding sustainable forest management (cf. CEN 2014). Biogenic carbon releases from burning wood in the production stage (modules A1 and A3) are reported as CO_2 emissions (+ 1).

The molar mass ratio of CO_2 to carbon equals the ratio of 44/12. In line with the guidelines of the International Panel of Climate Change (IPCC 2006), the carbon content in absolutely dry wood is assumed to be 50%. Thus, the equation for estimating the CO_2-effects of wood flows (CO_2, wood) is:

$\mathrm{CO_2,\ wood} = \mathrm{mw}, 0\%\ \mathrm{mc} * 0.5 * 44/12.$

where: mw, 0% mc = mass of wood, 0% moisture content (mc).

2.3 Functional units

In principle, buildings consist of outer wall, inner wall, ceiling and roof elements. Frame constructions form the load bearing part of a prefabricated timber frame house, whereas wood-based panels stiffen the building (Fritzen 2014). Commonly used materials are construction wood (usually kiln-dried softwood and engineered softwood products), wood-based panels [such as particleboard and oriented strand board (OSB)], gypsum plasterboard, insulation material (for instance wood fiber insulation board, glass wool or stone wool) and foils. Commonalities and differences between the building elements are illustrated in detail in Fig. 3.

The composition of the selected functional units in this study represents the production volume weighted averages from data collected at 13 house manufacturing sites. Principally, the LCA was conducted for the four basic building elements as well as for a whole representative building containing these elements. The functional units are defined as follows:

- 1 m² average outer wall element
- 1 m² average inner wall element
- 1 m² average storey ceiling element
- 1 m² average roof element
- 1 average prefabricated timber house [143 m² nla (net living area)]

The average U-value was evaluated to be 0.15 W/m² K for outer walls and 0.21 W/m² K for the roof elements. For the average inner wall both load-bearing and non-load-bearing walls are considered.

Additional to the LCA for single building elements a prefabricated timber house providing 143 m² nla was investigated (as the average of all participating companies) reflecting a combination of the single elements of the buildings' core and shell as well as doors, windows and floor screed.

2.4 Prefabrication of building elements (module A3)

The following process description is based on factory visits and represents an average technology for prefabricating the building elements. Generally speaking, the manufacturing of wall elements as well as roof- and ceiling elements respectively as shown in Fig. 2 is only slightly different.

Their production phase starts with the manufacturing of construction timber and panels. The key step of the further process is the assembly of the construction timber and the panels at butterfly turning tables in horizontal level. Usually, there are several tables, connected by runways, which are used for the following steps. Firstly, the construction timber is assembled and one side is planked with wooden panels. After turning around, empty conduits for electric installation as well as insulation material are applied. Subsequently, the second side is planked with wooden panels or gypsum plasterboards (wall elements). In the case of roof elements, battens are mounted. Then, the elements are turned into vertical level. At this stage, the inner wall-, roof- and ceiling elements are ready for packaging and transport. In vertical level, the plastering and other facade work is carried out and windows and doors are assembled to the outer wall elements. Due to the high weight of the elements, transports within the factory are mostly done by cranes and overhead tracks.

2.5 Transport of the building elements and construction of the building (modules A4-5)

The transport of the building elements from factory to construction site is carried out with lorries. At the construction site, a crane lifts the building elements in their final position where they get fixed with fasteners to other parts of the building. This is done by cordless screw drivers and drilling machines. The building elements are grounded, joints between plasterboards get filled. In addition, some manufacturers do plastering work partly onsite. The screed gets laid and dried. Except the drying of the screed, all work can mostly be done within 2 days.

2.6 Data collection

The data collection was carried out at 13 factory sites of 12 companies which belong to the German Association of Prefabricated Construction (BDF). Each data set represents the annual production of a participating company. Standardized questionnaires were sent out to obtain the input and output

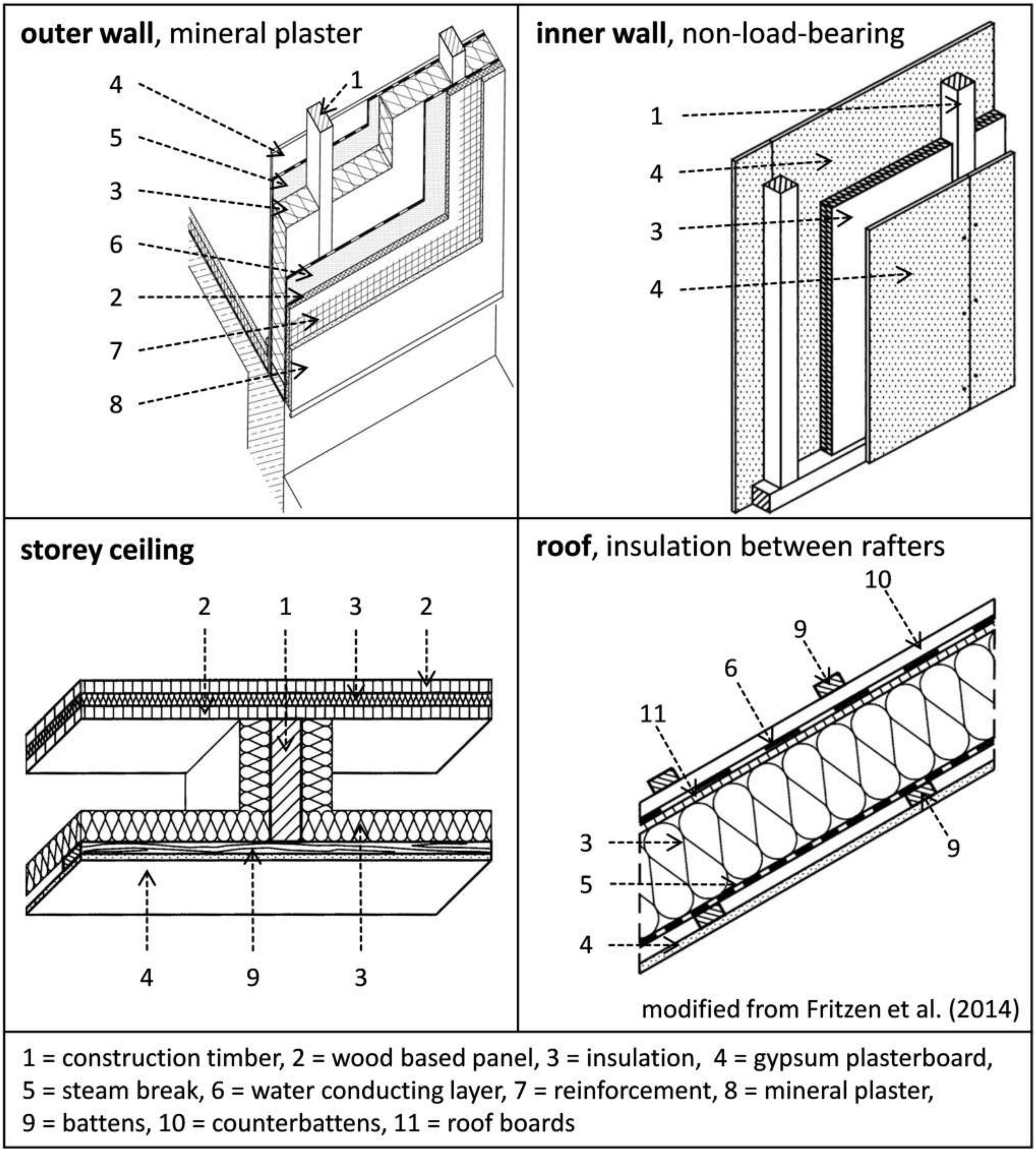


Fig. 3 Examples for standard building elements: outer wall, inner wall, storey ceiling and roof

flows of the factories representing the foreground system (module A3). The companies were asked to provide information on production volumes, energy generation, used raw materials and semi-finished products respectively, operational equipment as well as waste flows. Furthermore, data on the transport of semi-finished products to the factories (module A2) and annual data on the transport of the building elements to construction sites (module A4) were requested. The obtained information on the construction sites (module A5) refer to the construction of one average building (143 m² nla).

2.7 Plausibility check and data allocation to the functional units

2.7.1 Factory level

2.7.1.1 Plausibility check of annual data Due to the unavailability of information on the mass or volume of the building elements at the factory gate, balances between the product-related input and output flows could not be arranged. However, the volumes of the semi-finished wood products that remain in the building elements were determined by subtracting the cut-offs from the input data. For each type of building element, the results were cross-checked with volumes derived from representative design drawings provided by the building manufacturers and the obtained numbers on the annually produced square meters for each type of building element (see Fig. 4). Outliers which deviated more than 25% from the volumes derived from the design drawings and the average volumes of all companies were adjusted to the value calculated on the basis of the design drawings. For further calculations, the adjusted values were used.

2.7.1.2 Allocation of the yearly factory data to the average building elements Except for fasteners and sealants, the assignment of the building materials to the production lines of the wall-, ceiling- and roof elements was done by the companies. The annual heating demand required could be recorded separately and was allocated to the yearly production volume of each building element by the particular share of the production line area. The electricity demand, the operational equipment as well as fasteners and sealants were assigned to the annual production volumes of wall-, roof- and ceiling elements by the particular share of the total production volume. Dividing the annual numbers by the total number of produced m² provided the LCI for 1 m² average building element of a company.

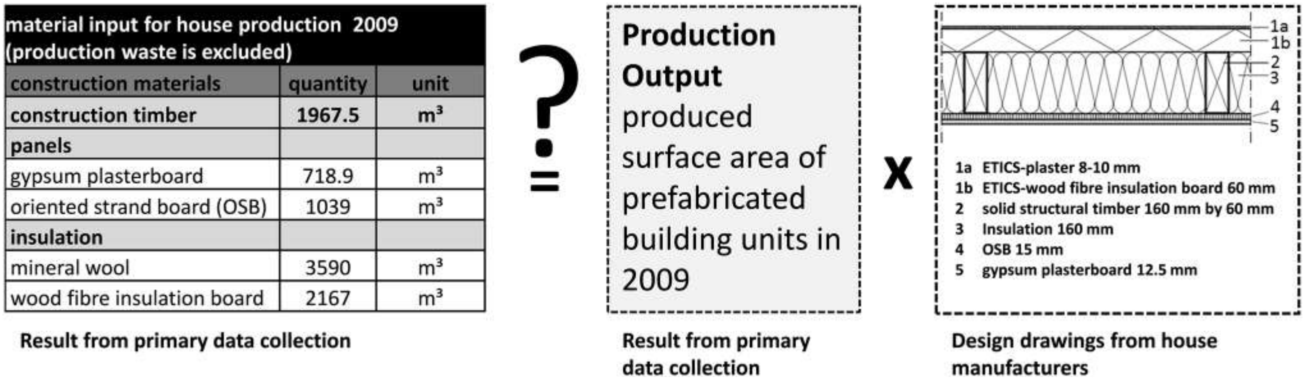
2.7.1.3 Upscaling to the average building (143 m²) For each factory site the upscaling on building level was done by multiplying the LCIs for the building elements with the dimensions of the respective average building. Additionally, windows, doors and floor screed were taken into account.

2.7.2 Sector level

The averaged compositions and LCIs of the functional units (see Sect. 2.3) were calculated by weighting the factory average with the production volume from the particular company in relation to the overall investigated quantities within this study. Finally, the sector-average of each building element as well as the average house are the totals of the 13 weighted factory averages.

2.8 Software, generic data and environmental assessment methodology

The LCA was conducted using the GaBi 6 software (PE International 2014). Generic data for solid wood and engineered wood consistent with EN 15804 was drawn from the LCA database ÖkoHolzBauDat (Rüter and Diederichs 2012; Diederichs 2014a, b) which includes representative average data for wooden building products from 43 German sawmills and 17 panel mills. Wenker et al. (2016) and IBU (2013a) provide average LCA data for doors and windows also in line with EN 15804. Furthermore, additional data was drawn from the GaBi Professional database, version 6.108 (PE International 2014) as well as ecoinvent v2.2 (ecoinvent Centre 2010). The data sources used for the production of raw materials and semi-finished products as well as the supply of energy in the prefabrication process and at the construction site are given in Sect. 3.2. The environmental impact assessment was achieved by using the CML methodology (Guinée et al. 2002) including the CML characterization factors as stated in the current version of EN 15804 (CEN 2013).



material input for house production 2009 (production waste is excluded)		
construction materials	quantity	unit
construction timber	**1967.5**	**m³**
panels		
gypsum plasterboard	718.9	m³
oriented strand board (OSB)	1039	m³
insulation		
mineral wool	3590	m³
wood fibre insulation board	2167	m³

Fig. 4 Plausibility check

3 Results

3.1 Results of plausibility check and data adjustment

The results of the plausibility check by volumes of the building materials at factory level are given in Table 1. Table 1a shows the mismatches between the input data provided by the companies and the data derived from construction drawings before the data adjustment. The reduced mismatches after the data adjustment according to Sect. 2.7.1 are provided in Table 1b.

3.2 Life cycle Inventories (LCIs)

Table 2 provides the inventory analyses of the average building elements and the average house. Whereas for building elements the LCIs are related to prefabrication in module A3 only, the LCI of the average house also includes the construction site (module A5). Data obtained from the factory sites is directly related to the manufacturing of the building elements. Material and energy flows caused by other main products also manufactured at these sites (e.g. wooden stairs) were not included in the data collection. The only data that could not be captured solely was the share of energy demand as well as operational resources and its supply chain regarding the coproduct wooden trim waste for sale. The contribution to the overall monetary revenue generated by this coproduct is less than 1%. Thus, in line with EN 15804, no allocation was done and energy demands as well as operating resources related to the coproduct were included into the LCAs of the functional units under study (conservative approach). The determined transport distances between the investigated factories and the construction sites can be seen in Table 3. The transport to construction site (module A4) is mostly carried out by 40 ton trucks. Additionally, 7.5 ton trucks are used. On average, the transport of the elements for one house requires 884 l diesel. The diesel consumption for the transport of the semi-finished products to the house manufactories (module A2) could not be provided by the companies. However, from the manufacturers' data a mass-weighted average distance of 220 km was calculated and linked with lorry-specific data from GaBi database.

Table 1 Deviations between queried total input volumes and total volumes on factory level derived from construction drawings before (a) and after (b) data adjustment

(a) Deviations of the total volumes before data adjustment		(b) Deviations of the total volumes after data adjustment	
Deviations [%]	Share of the factories [%]	Deviations [%]	Share of the factories [%]
± 0–11	46	± 0–4	30
± 24–36	31	± 5–13	54
± 44–46	23	± 25–35	16

3.3 Life cycle impact assessment

Results of the life cycle impact assessment (LCIA) are shown in Table 4. In addition to the accounted modules, the manufacturer-specific deviations are given for the environmental impact categories.

3.4 Detailed GWP results for the average house

The total amount of fossil CO_2 eq. emissions from the product and construction stage (module A1–A5) of the average house is 29.618 kg. The respective shares of the modules A1, A2 and A3–A5 can be seen in Fig. 5. The wood inherent carbon balance is expressed as CO_2 inputs and outputs. For the production of semi-finished wood products – 30.507 kg of biogenic CO_2 is transferred to the product system (module A1) (see Fig. 5). Of this, 5606 kg CO_2 is emitted by burning purchased waste wood and trim waste for heat and energy generation (A1). Wooden trim waste also accrues in the prefabrication of the building elements and is almost exclusively burned for heat and energy generation in the house manufactories (module A3). According to EN 15804, the herein contained biogenic carbon as well as the carbon within purchased waste wood has to be taken into account as input to and output from the product system in module A3 (± 5456 kg CO_2).

3.5 Dominance analysis

In relation to the overall German impacts, i.e. after normalization to the overall German emissions using GaBi 6 software (PE International 2014), the contributions to the environmental indicators global warming potential (GWP), acidification potential (AP) and the abiotic resource depletion potential (ADPe) appear to be most important. The highest impacts are caused by the manufacturing processes of the included building materials (module A1) (see Fig. 6). However, in GWP and AP category around 30% of the total impacts are caused by the prefabrication of the building elements, their transport and the processes at the construction site (modules A2–A5). With 40%, the modules A2–A5 have the highest environmental impact for the indicator eutrophication potential (EP) (not shown in Fig. 6). A more detailed view on the main contributors to these categories is given in Table 5.

Table 2 LCI for the manufacturing of building elements as well as manufacturing and construction of an average house (143 m² nla), comprising inputs and outputs

	(a) 1m² OW	(b) 1m² IW	(c) 1m² RE	(d) 1m² CE	(e) 1 house	Unit	Background database used
Inputs							
Semi-finished building materials							
Solid wood	22.15	11.42	20.80	19.98	9552.96	kg	ÖKOHOLZBAU.DAT
Engineered wood	13.65	15.90	1.81	15.89	5984.28	kg	ÖKOHOLZBAU.DAT
Gypsum boards	10.52	16.43	8.98	9.06	5508.01	kg	GaBi Professional
Insulation materials	7.46	1.15	4.43	2.21	2029.06	kg	GaBi Professional, ecoinvent
Plaster	6.10	–	–	–	894.78	kg	GaBi Professional
Gas concrete	0.44	–	–	–	63.97	kg	GaBi Professional
Bricks and mortar	14.51	–	–	–	2125.80	kg	GaBi Professional
Fastening materials	0.82	0.82	0.82	0.82	411.37	kg	GaBi Professional
Sealants	0.41	0.41	0.41	0.41	206.64	kg	GaBi Professional
Vapour barrier/ water conducting layer	0.26	–	0.47	–	132.39	kg	GaBi Professional
Laquer, paint, wood preservative	0.31	–	0.11	–	57.74	kg	GaBi Professional, ecoinvent
Floor screed	–	–	–	–	12056.00	kg	GaBi Professional
Entry door	–	–	–	–	1	pcs	Wenker et al. 2016
Windows	–	–	–	–	18	pcs	IBU 2014
Window board	–	–	–	–	197.9	pcs	GaBi Professional
Interior doors	–	–	–	–	7	pcs	Wenker et al. 2016
Energy demand							
Electricity	27.42	27.42	27.42	27.42	13752.72	MJ	GaBi Professional
From oil and natural gas	13.70	12.99	12.81	12.88	6582.98	MJ	GaBi Professional
Electricity demand on con-struction site (module A5)	–	–	–	–	7465.40	MJ	GaBi Professional
Wooden trim waste from own production and purchased postconsumer waste wood for energy production	5.83	6.09	5.33	5.22	2811.54	kg	GaBi Professional
Diesel for forklifts	0.07	0.07	0.07	0.07	35.11	kg	GaBi Professional
Diesel for crane on con-struction site (module A5)	0.17	0.17	0.17	0.17	87.60	kg	GaBi Professional
Operational equipment							
Fresh water	23.29	23.29	23.29	23.29	11680.13	kg	GaBi Professional
Fresh water on construction site	1.26	1.26	1.26	1.26	630.00	kg	GaBi Professional
Oil, grease, cleaning supp-lies, sanding belts,etc	0.02	0.02	0.02	0.02	12.31	kg	GaBi Professional
Package of semi-finished products and operational equipment							
PE foil	1.10	0.53	1.25	1.03	490.77	kg	GaBi Professional
Polystyrene	0.14	0.07	0.15	0.13	60.19	kg	GaBi Professional
Cardboard	0.25	0.12	0.28	0.23	110.34	kg	GaBi Professional
Package for the transport of the building elements to construction site							
PE foil	0.28	0.21	0.24	0.23	120.00	kg	GaBi Professional
Outputs							
Products							
Main Product	73.94	45.15	36.29	47.66	143.13	kg/nla*	
Coproduct–wooden trim waste from pre-fabrica-tion in house manufactory	0.61	0.47	0.39	0.61	261.41	kg	
Emissions							
From burning energy carriers	From background data						GaBi Professional, ÖKOHOLZBAU.DAT
From burning diesel							
Setting of adhesives							

Table 2 (continued)

	(a) 1m² OW	(b) 1m² IW	(c) 1m² RE	(d) 1m² CE	(e) 1 house	Unit	Background database used
Factory waste							
Packaging, mixed waste	2.11	1.75	3.12	2.24	1151.44	kg	GaBi Professional
Ashes	From background data						GaBi Professional
Waste from construction site							
Demolition waste	2.09	–	–	–	1138.30	kg	GaBi Professional
PE-foil (packaging)	0.28	0.21	0.24	0.23	120	kg	GaBi Professional

*for (a) outer walls (OW), (b) inner walls (IW) (c) roof elements (RE), (d) ceiling elements (CE) the unit is kg, in case of (e) 1 house the unit is nla (net living area)

Table 3 Transport distances between house manufacturers and construction sites

Transport distance	Share
Germany	89%
< 50 km	8%
50–200 km	19%
200–400 km	41%
> 400 km	21%
Europe	ca. 10%
others	ca. 1%

4 Discussion

4.1 Data quality and representativeness

To evaluate the data quality and hence the quality of the impact assessment results, information on representativeness (technological, geographical, temporal) and completeness of the collected data is given.

In 2009, the 12 manufacturing sites under study produced building elements for 3543 timber houses. In this year a total of 9736 prefabricated timber houses were built in Germany (StBA 2013). Therefore, the study covers 36% of the sector. According to the data of the Federal Statistical Office, the German prefabricated building sector counted 491 enterprises in 2009, of which 18 enterprises employed more than 50 people (StBa 2010). Each company considered by this study has more than 50 employees, so the coverage for companies with more than 50 employees is at 67%. Hence, the LCA data can be considered as representative for large enterprises in particular. Summing up, the data provided in this study is characterized by a high technological as well as a high geographical representativeness looking at whole Germany. All collected input and output data represents the participating companies' total production of the year 2009. The majority of the used background data sets is not older than 7 years. Only 4 background data sets origin from the years 2005 and 2000. However, none of the materials to which the latter background data was applied showed dominant environmental impacts.

For determining the LCIs of the prefabrication process (within the 12 participating companies, module A3) and of the construction site (A5), no identified material or energy flows were cut. Since no background data for the LCIA of tyres (of the forklifts) were available, they could not be considered for impact assessment.

4.2 Sensitivity analysis

The sensitivity of the LCIA was tested by changing the quantities of solid wood, wood-based panels, gypsum plasterboards and insulation, which were calculated for the functional units as described in Sect. 2.7, to the quantities derived from construction drawings. All other parameters remained unchanged. As shown in Fig. 7, the differences in the amounts of building materials have a relatively little effect on the results. The maximum deviation of 10.3% occurs for the indicator "photochemical oxidation creation potential" (POCP).

4.3 Results in the context of other studies

In line with state-of-the-art European standards, the study provides average LCA data for the product stage (module A1–A3) of 1 m² inner and outer wall, ceiling and roof element as well as for the product and construction stage (A1–A5) of a family house. The extensive data collection that has been conducted ensures robust LCI-data for the modules A3–A5. Table 4 and Fig. 6 show that each of these modules has important shares of the total environmental impacts and energy demands.

Table 6 gives a modular comparison of fossil CO_2 eq. emissions per m² nla as presented by this study with results reported by Peñaloza et al. (2013) and Takano et al. (2015). Although these authors studied multi-storey timber buildings, certain aspects can be discussed comparatively. The results of module A1 are in the same order of magnitude. The relatively high CO_2 eq. emissions in Takano et al. (2015) are most likely due to the fact that the building

Table 4 Environmental impact assessment and primary energy demand. Selected modules and parameters according to EN 15804

Parameter	Units	Raw material supply (A1)	Transport (A2)	Manufacturing (A3)	Total cradle to gate (A1–A3)	Max. deviation −%/+% (A1–A3)	Reuse-recovery-recycling-potential (D)
Results of the LCA—environmental impacts and primary energy demand of 1 m² outer wall							
GWP	[kg CO_2-eq.]	− 1.58E+01	1.20E+00	1.29E+01	− 1.74E+00	− 35.1/+135.9	− 4.40E-01
ODP	[kg CFC11-eq.]	1.82E-06	1.48E-12	2.06E-07	2.03E-06	− 60.3/ + 46.4	− 1.80E-11
AP	[kg SO_2-eq.]	1.37E-01	5.30E-03	3.24E-02	1.75E-01	− 31.2/+99.0	− 6.26E-04
EP	[kg PO_4^{3-}-eq.]	2.01E-02	1.45E-03	5.99E-03	2.75E-02	− 36.4/+116.2	− 7.47E-05
POCP	[kg Ethen-eq.] eq.]	2.56E-02	− 2.01E-03	6.23E-03	2.98E-02	− 58.3/+42.6	− 5.79E-05
ADPE	[kg Sb-eq.]	6.63E-04	6.21E-08	2.54E-06	6.65E-04	− 21.8/+70.0	− 5.23E-08
ADPF	[MJ]	6.54E+02	1.64E+01	1.02E+02	7.72E+02	− 25.8/+ 117.5	− 5.80E+00
PERE	[MJ]	1.84E+02	1.25E+00	1.48E+02	3.33E+02		− 4.40E-01
PERM	[MJ]	6.25E+02	0.00E+00	− 6.07E+00	6.19E+02		− 1.80E-11
PENRE	[MJ]	6.92E+02	1.64E+01	6.91E+01	7.78E+02		− 6.26E-04
PENRM	[MJ]	4.97E+01	0.00E+00	5.85E+01	1.08E+02		− 7.47E-05
Results of the LCA—environmental impacts and primary energy demand of 1 m² inner wall							
GWP	[kg CO_2-eq.]	− 2.72E+01	3.85E-01	9.20E+00	− 1.76E+01	− 27.9/+38.0	− 3.30E-01
ODP	[kg CFC11-eq.]	1.41E-06	4.75E-13	2.00E-07	1.61E-06	− 76.7/+17.6	− 1.35E-11
AP	[kg SO_2-eq.]	5.10E-02	1.70E-03	2.67E-02	7.94E-02	− 32.6/+48.1	− 4.70E-04
EP	[kg PO_4^{3-}-eq.]	9.38E-03	4,65E-04	4.99E-03	1.48E-02	− 43.1/+47.3	− 5.60E-05
POCP	[kg Ethen-eq.]	1.23E-02	− 6.45E-04	3.56E-03	1.52E-02	− 57.4/+67.8	− 4.34E-05
ADPE	[kg Sb-eq.]	4.85E-04	1.99E-08	2.21E-06	4.88E-04	− 35.7/+65.9	− 3.92E-08
ADPF	[MJ]	2.41E+02	5.25E+00	8.40E+01	3.31E+02	− 30.1/+37.9	− 4.35E+00
PERE	[MJ]	8.71E+01	4.02E-01	1.51E+02	2.38E+02		− 5.18E-01
PERM	[MJ]	4.74E+02	0.00E+00	− 5.93E+00	4.68E+02		0.00E+00
PENRE	[MJ]	2.87E+02	5.27E+00	7.66E+01	3.69E+02		− 5.08E+00
PENRM	[MJ]	5.96E+00	0.00E + 00	3.10E+01	3.69E+01		0.00E+00
Results of the LCA—environmental impacts and primary energy demand of 1 m² roof element							
GWP	[kg CO_2-eq.]	− 2.03E+01	3.34E-01	1.06E+01	− 9.31E+00	− 50.6/+27.6	3.77E-01
ODP	[kg CFC11-eq.]	1.09E-06	4.12E-13	1.75E-07	1.26E-06	− 65.1/+19.2	− 1.54E-11
AP	[kg SO_2-eq.]	7.02E-02	1.48E-03	2.56E-02	9.72E-02	− 33.3/+21.3	− 5.37E-04
EP	[kg PO_4^{3}-eq.]	1.07E-02	4.03E-04	4.70E-03	1.58E-02	− 40.5/+22.8	− 6.40E-05
POCP	[kg Ethen-eq.]	1.03E-02	− 5.59E-04	4.01E-03	1.37E-02	− 33.2/+28.2	-4.96E-05
ADPE	[kg Sb-eq.]	4.03E-04	1.73E-08	2.24E-06	4.05E-04	− 54.9/+13.0	− 4.48E-08
ADPF	[MJ]	2.49E+02	4.56E+00	8.23E+01	3.36E+02	− 36.7/+21.2	− 4.97E+00
PERE	[MJ]	9.32E+01	3.49E-01	1.31E+02	2.25E+02		− 5.92E-01
PERM	[MJ]	4.13E+02	0.00E+00	7.23E+00	4.20E+02		0.00E+00
PENRE	[MJ]	2.68E+02	4.57E+00	4.80E+01	3.21E+02		− 5.80E+00
PENRM	[MJ]	2.07E+01	0.00E+00	5.71E+01	7.78E+01		0.00E+00
Results of the LCA—environmental impacts and primary energy demand of 1 m² ceiling element							
GWP	[kg CO_2-eq.]	− 3.18E+01	4.46E-01	1.01E+01	− 2.12E+01	− 48.3/+18.4	− 3.62E-01
ODP	[kg CFC11-eq.]	1.58E-06	5.50E-13	1.71E-07	1.75E-06	− 56.8/+24.5	− 1.48E-11
AP	[kg SO_2-eq.]	6.60E-02	1.97E-03	2.46E-02	9.25E-02	− 33.3/+33.8	− 5.14E-04
EP	[kg PO_4^{3-}-eq.]	1.14E-02	5.39E-04	4.50E-03	1.64E-02	− 36.9/+30.5	− 6.14E-05
POCP	[kg Ethen-eq.]	1.28E-02	− 7.46E-04	3.16E-03	1.52E-02	− 38.3/+46.1	− 4.75E-05
ADPE	[kg Sb-eq.]	4.30E-04	2.30E-08	2.21E-06	4.32E-04	− 64.4/+30.0	− 4.29E-08
ADPF	[MJ]	2.95E+02	6.08E+00	8.15E+01	3.83E+02	− 46.6/+51.2	− 4.77E+00
PERE	[MJ]	1.13E+02	4.65E-01	1.33E+02	2.46E+02		− 5.68E-01
PERM	[MJ]	5.79E+02	0.00E+00	− 6.36E+00	5.72E+02		0.00E+00
PENRE	[MJ]	3.33E+02	6.10E+00	5.06E+01	3.90E+02		− 5.56E+00
PENRM	[MJ]	2.07E+01	0.00E+00	5.35E+01	7.42E+01		0.00E+00

Table 4 (continued)

Parameter	Units	Raw material supply (A1)	Transport (A2)	Manufacturing (A3)	Total cradle to gate (A1–A3)	Transport of building elements (A4)	Construction site (A5)	Max. deviation -%/+% (A1–A5)	Reuse-recovery-recycling-potential (D)
Results of the LCA—environmental impacts and primary energy demand of 1 house (143 m² nla.)									
GWP	[kg CO_2-eq.]	− 4.45E+03	2.78E+02	5.07E+03	8.94E+02	2.64E+03	1.89E+03	− 31.2/+31.7	− 1.89E+02
ODP	[kg CFC11-eq.]	8.61E-04	3.43E-10	9.22E-05	9.54E-04	4.99E-09	1.28E-07	− 48.6/+15.2	− 7.70E-09
AP	[kg SO_2-eq.]	6.22E+01	1.23E+00	1.29E+01	7.64E+01	1.18E+01	3.64E+00	− 31.1/+20.4	− 2.68E-01
EP	[kg PO_4^{3-}-eq.]	9.60E+00	3.36E-01	2.39E+00	1.23E+01	3.18E+00	6.66E-01	− 29.6/+25.3	− 3.20E-02
POCP	[kg Ethen-eq.]	9.77E+00	− 4.65E-01	2.05E+00	1.14E+01	− 4.36E+00	− 3.43E-01	− 75.3/+39.8	− 2.48E-02
ADPE	[kg Sb-eq.]	3.11E-01	1.44E-05	1.12E-03	3.13E-01	1.39E-04	3.52E-04	− 21.8/+20.0	− 2.24E-05
ADPF	[MJ]	2.49E+05	3.79E+03	4.17E+04	2.95E+05	3.59E+04	1.73E+04	− 27.9/+20.3	− 2.49E+03
PERE	[MJ]	7.97E+04	2.90E+02	6.57E+04	1.50E+05	2.76E+03	5.12E+03		− 2.96E+02
PERM	[MJ]	2.61E+05	0.00E+00	− 1.48E+03	2.60E+05	0.00E+00	0.00E+00		0.00E+00
PENRE	[MJ]	2.72E+05	3.80E+03	2.82E+04	3.04E+05	3.60E+04	2.62E+04		− 2.90E+03
PENRM	[MJ]	1.98E+04	0.00E+00	2.51E+04	4.49E+04	0.00E+00	0.00E+00		0.00E+00

GWP global warming potential, *ODP* (stratospheric) ozone depletion potential, *AP* acidification potential of land and water, *EP* eutrophication potential, *POCP* formation potential of tropospheric ozone, *ADPE* abiotic depletion potential (ADP elements) for nonfossil resources; *ADPF* abiotic depletion potential (ADP fossil fuels) for fossil resources, *PERE* use of renewable primary energy excluding renewable primary energy resources used as raw materials, *PERM* use of renewable primary energy resources used as raw materials, *PENRE* use of nonrenewable primary energy excluding nonrenewable primary energy resources used as raw materials, *PENRM* use of nonrenewable primary energy resources used as raw materials

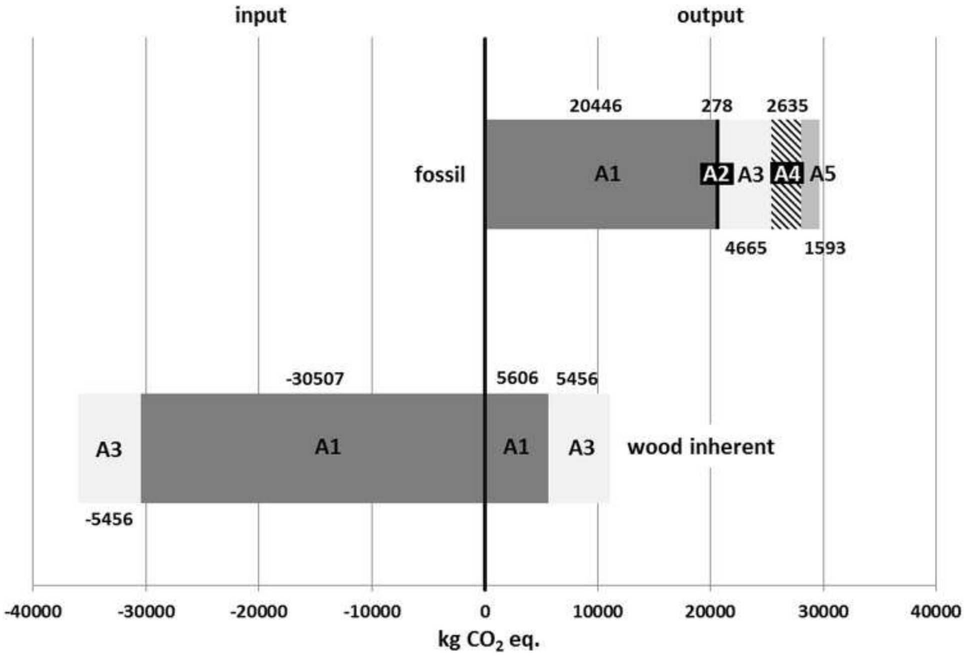


Fig. 5 Balance of fossil and wood inherent CO_2-eq. of the average house

assessed in this case study also included a basement of a reinforced concrete structure. The higher resource efficiency of a multi-storey building, i.e. less building materials are needed for creating 1 m² nla, is probably the reason for the lower values in Peñaloza et al. (2013). For the transport of building materials and the prefabrication (modules A2–A3) the results of Takano et al. (2015) are quite similar to those presented in Sect. 3.

In the case study by Peñaloza et al. (2013), the building elements were transported 1306 km to the construction site (module A4). For assessing the environmental impact of module A4 the amount of transportation was defined by

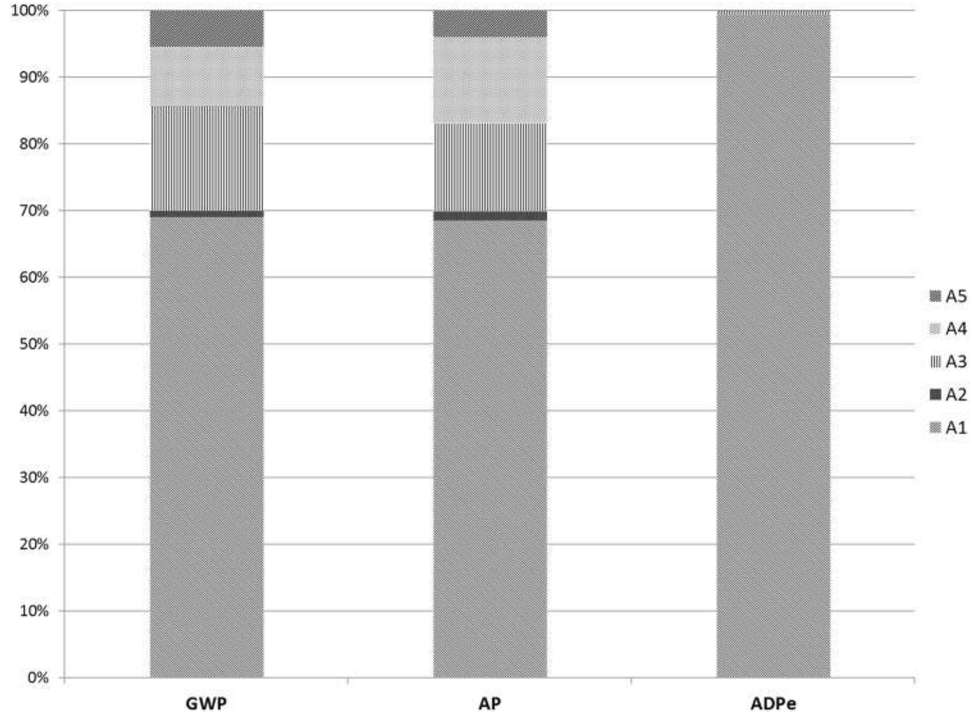


Fig. 6 Shares of the impacts of the manufacturing and construction of an average house for the indicators GWP, AP and ADPe. CO_2 related to the wood inherent carbon balance, which is neutral over the whole life cycle, is not considered

Table 5 Main contributors to the categories GWP, AP and ADPe for an average house (modules A1-A5)

GWP (kg CO_2 eq.)	%	AP (kg SO_2 eq.)	%	ADPE (kg Sb eq.)	%
Doors and windows (A1)	17.94	Doors and windows (A1)	22.13	Gypsum boards (A1)	33.19
Mortar and floor screed (A1)	9.88	Transport of building elements to construction site (A4)	12.93	Doors and windows (A1)	26.11
Insulation (A1)	9.02	Insulation (A1)	11.03	Fasteners (A1)	20.05
Wood based panels (A1)	9.02	Solid wood (A1)	10.60	Insulation (A1)	7.83
Transport of building elements to construction site (A4)	8.94	Burning wood in house manufactory (A3)	7.24	Mortar and floor screed (A1)	4.30
Electricity demand of pre-fabrication in house manufactory (A3)	7.94	Wood based panels (A1)	6.64	Plaster (A1)	3.97
Solid wood (A1)	6.21	Mortar and floor screed (A1)	4.43	Others	4.55
Processes at construction site (A5)	5.41	Electricity demand of pre-fabrication in house manufactory (A3)	4.22		
Polyurethane foam (A1)	4.51	Processes at construction site (A5)	3.92		
Gypsum boards (A1)	3.78	Fasteners (A1)	3.70		
Fasteners (A1)	3.63	Others	13.16		
Production waste of house manufactory (A3)	3.46				
Others	10.26				

the weight of the building elements. Peñaloza et al. (2013) mentioned that it might be more appropriate choosing the volume instead. However, both approaches (weight/volume) are approximate ones. How much volume of building element fits into a truck depends on the dimensions of the components in relation to the volume of the specific trailer. To obtain more precise results, the companies were questioned about the annual diesel demand for the transport of the building elements and the truck types used. On average, the building elements are transported to the construction site 350 km (see Table 3) with 40 and 7.5 ton trucks. In many cases, the trucks drive back empty. The required transport for one house is carried out by 5–8 trucks and requires 884 l diesel on average. It is remarkable that—compared to the study by Peñaloza et al. (2013)—the GWP results of module A4 are almost twice as high (per m² nla), although the average distance assessed within this study is 3.7 times shorter. Even if the transports of building elements for a

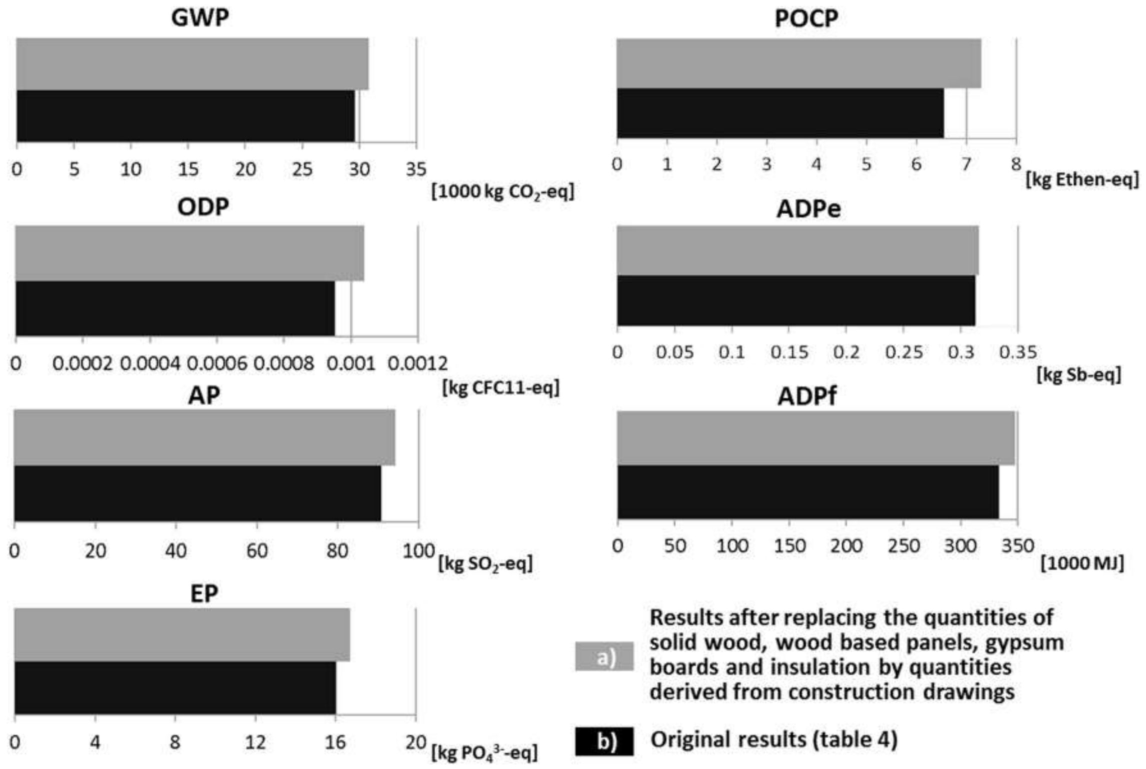


Fig. 7 Results of the sensitivity analysis

Table 6 GWP results of the present study compared with values given by Peñaloza et al. (2013) and Takano et al. (2015)

	A1	Sum A2–A3	A4	A5	Sum A4–A5	Unit
Results of the present study	143	37	18	13	31	kg CO_2 eq.
Penaloza et al. (2013)	142–146	–	10	11	21	
Takano et al. (2015)	371	40	–	–	42	

multi-storey house is not directly comparable to those for a family house, the results indicate that in the case of bulky cargo, the assessment of the transport by mass as done by Peñaloza et al. (2013) underestimates the actual environmental impacts.

The comparatively high GWP results of the module A5 in Takano et al. (2015) might be due to the additional energy demand needed for the construction works for the basement, which are not within the system boundaries of the present study and also not taken into account by Peñaloza et al. (2013).

4.4 Prefabrication within the modular principle of EN 15804

Originally, the modular concept of EN 15804 and EN 15978 was intended for the assessment of the onsite construction method of buildings (see Fig. 8a). According to this concept, module A1 accounts for the raw material supply and A2 for the transport of the raw materials. The core product stage is terminated by module A3, which contains the manufacturing of the building materials. Consequently, the system boundary of the product stage would then be defined by the gate of the building material manufacturers. In the construction stage, the building materials are subsequently transported to the construction site within module A4 and the construction work itself is taken into account by A5.

In the present study, the raw material supply and the manufacturing of building products are summarized in module A1, the transport of building materials incorporated in the building elements is accounted for in A2 and the manufacturing of the building elements is considered in A3 (see Fig. 8b). Consequently, module A4 contains the transport of the building elements. The construction work, which is mainly the assembling of the building elements onsite, is accounted for in module A5. This approach ensures that the boundary between product and construction stage remains at the factory gate, also for prefabricated building elements.

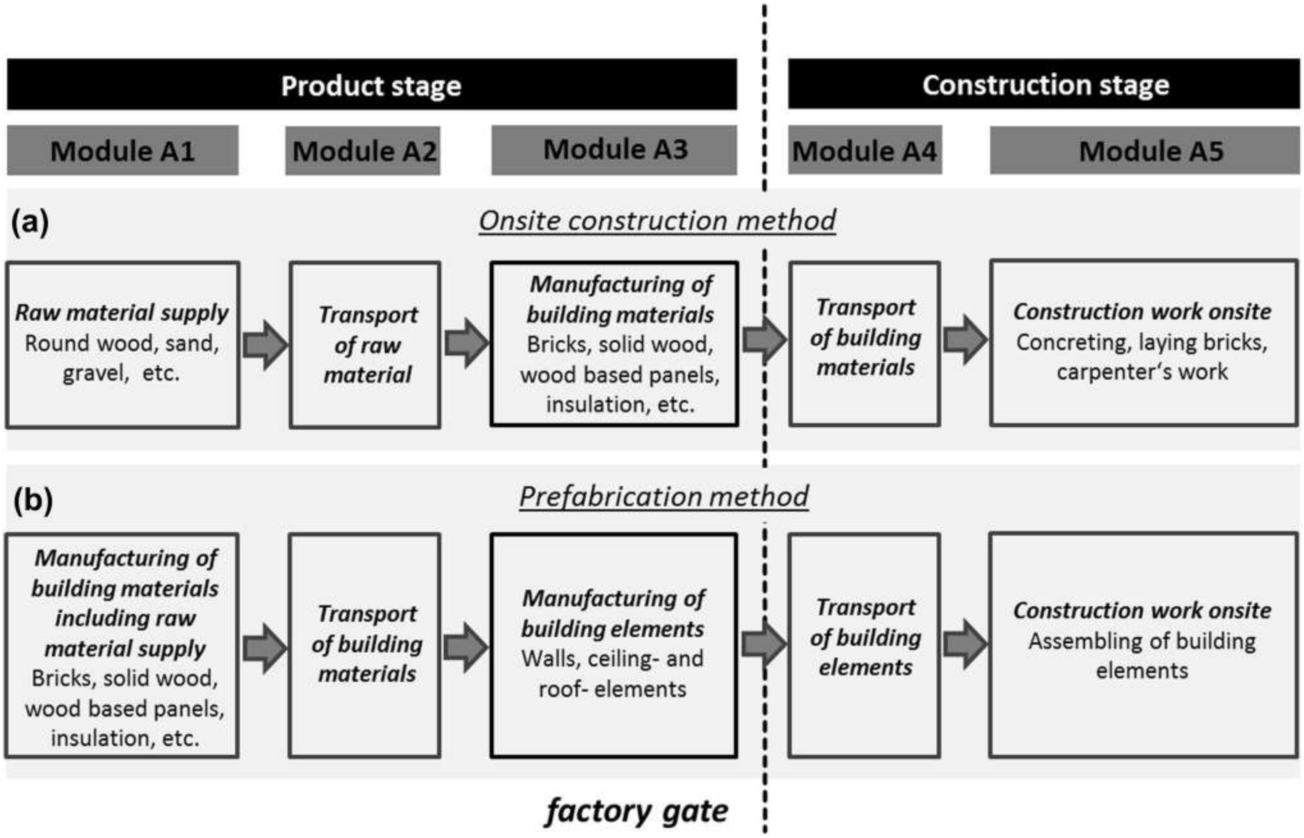


Fig. 8 Modular principle of EN 15804/EN15987 applied to the onsite construction method (**a**) and the prefabrication method (**b**)

As mentioned in Chap. 1.2, Takano et al. (2015) pointed out that this approach distorts the results of the mandatory modules A1–A3 for prefabricated timber houses in favor of an onsite construction system and makes the comparison of the product stage difficult. On that point, the authors agree with Takano et al. (2015). Some assessment schemes for sustainable buildings (e.g. BNB and DGNB system) which are based on EN 15978 and EN 15804 consider the product (modules A1–A3) and end-of-life stages (C1–C4) only. If the construction stage (modules A4–A5) is not inside the system boundaries, the onsite system does not include processes for constructing walls, the roof and ceilings, whereas in case of the prefabrication system the manufacturing of these building elements is accounted for.

On the other hand, the partitioning of the construction process in the modules prefabrication (A4-A5: P) and onsite construction (A4-5: O) (see Takano et al. 2015) leads to a problem of definition. Simply speaking, where does manufacturing end and where does prefabrication start? In recent years, many EPDs for building elements such as wall and ceiling elements, doors, windows and partitioning systems (IBU 2012, 2013a, b, 2014, 2015) were published by adapting the modular principle of EN 15804 for the product stage as shown in Fig. 8b. In all these studies, prefabrication processes were accounted for in module A3. Due to the increasing level of prefabrication, a consistent distinction in processes which are actually carried out onsite and processes belonging to the manufacturing seem to be difficult. Therefore, even in the case of prefabrication systems it is proposed to draw the line between product stage and construction stage at the factory gate, as it is an unambiguous point of the product system. To avoid favoring the onsite construction system it is strongly recommended taking into account in any case the construction stage (modules A4–A5) as well and not considering the product stage only.

4.5 Lowering the environmental impacts of the average house

There are multiple options for lowering the environmental impacts of a prefabricated house by substituting particular building materials. The biggest potentials lie in the substitution of plastic windows, mineral wool and gypsum boards (Tables 5, 7). The average house includes 12 plastic windows, 4 wood windows and 2 wood-aluminium windows. Using 18 wood windows instead lowers the total GWP of the average house by 2.5%. 70% of the insulation material used is mineral wool. Its comparatively high environmental

Table 7 Main contributors to the categories GWP, AP and ADPe for each building element

GWP (kg C0$_2$ eq.)	%	AP (kg SO$_2$ eq.)	%	ADPE (kg Sb eq.)	%
1 m² outer wall					
Insulation (A1)	18.84	Insulation (A1)	19.41	Gypsum boards (A1)	34.82
Wood based panels (A1)	17.07	Solid wood (A1)	13.98	Fasteners (A1)	33.47
Transport of building elements to construction site (A4)	9.36	Transport of building elements to construction site (A4)	13.19	Plaster (A1)	14.52
Solid wood (A1)	8.31	Solid wood panels (A1)	11.15	Insulation (A1)	10.85
Electricity demand of pre-fabrication in house manufactory (A3)	8.30	Burning wood in house manufactory (A3)	7.38	Others	6.34
Fasteners (A1)	6.05	Fasteners (A1)	6.00		
Bricks (A1)	5.46	Electricity demand of pre-fabrication in house manufactory (A3)	4.29		
Production waste of house manufactory (A3)	5.42	Plaster (A1)	3.77		
Plaster (A1)	4.33	Bricks (A1)	3.51		
Gypsum boards (A1)	4.31	Vapour barrier (A1)	2.96		
Others	12.55	Gypsum boards (A1)	2.72		
		Others	11.64		
1 m² inner wall					
Wood based panels (A1)	18.32	Burning wood in house manufactory (A3)	15.18	Gypsum boards (A1)	65.36
Electricity demand of pre-fabrication in house manufactory (A3)	15.30	Wood based panels (A1)	14.78	Fasteners (A1)	25.64
Gypsum boards (A1)	10.78	Transport of building elements to construction site (A4)	13.83	Production waste of house manufactory (A3)	4.26
Transport of building elements to construction site (A4)	9.71	Solid wood (A1)	11.77	Insulation (A1)	3.22
PU foam (A1)	8.72	Electricity demand of pre-fabrication in house manufactory (A3)	8.00	Others	1.52
Fasteners (A1)	7.02	Gypsum boards (A1)	7.79		
Solid wood (A1)	6.95	Insulation (A1)	7.18		
Burning wood in house manufactory (A3)	4.95	Fasteners (A1)	7.04		
Insulation (A1)	4.66	Construction site (A5)	2.80		
Production waste of house manufactory (A3)	3.93	Others	11.63		
Energy from oil and natural gas (A3)	3.23				
Others	6.43				
1 m² roof					
Transport of building elements to construction site (A4)	17.00	Transport of building elements to construction site (A4)	21.57	Gypsum boards (A1)	41.38
Insulation (A1)	15.28	Insulation (A1)	20.02	Fasteners (A1)	30.84
Electricity demand of pre-fabrication in house manufactory (A3)	13.07	Solid wood (A1)	17.52	Insulation (A1)	20.58
Solid wood (A1)	11.98	Burning wood in house manufactory (A3)	10.06	Production waste of house manufactory (A3)	5.01
Production waste of house manufactory (A3)	7.59	Electricity demand of pre-fabrication in house manufactory (A3)	6.09	Others	2.19

Table 7 (continued)

GWP (kg $C0_2$ eq.)	%	AP (kg SO_2 eq.)	%	ADPE (kg Sb eq.)	%
PU foam (A1)	7.41	Fasteners (A1)	5.34		
Fasteners (A1)	5.97	Vapour barrier (A1)	3.18		
Gypsum boards (A1)	4.70	Gypsum boards (A1)	3.10		
Burning wood in house manufactory (A3)	3.64	Product package (A3)	2.26		
Vapour barrier (A1)	2.86	Others	10.86		
Energy from oil and natural gas (A3)	2.74				
Others	7.76				
1 m² ceiling					
Wood based panels (A1)	19.09	Transport of building elements to construction site (A4)	21.06	Gypsum boards (A1)	39.66
Transport of building elements to construction site (A4)	14.50	Solid Wood (A1)	16.59	Fasteners (A1)	28.94
Electricity demand of pre-fabrication in house manufactory (A3)	11.89	Wood based panels (A1)	13.11	Mortar (A1)	18.25
Solid wood (A1)	9.57	Insulation (A1)	10.11	Insulation (A1)	6.83
Insulation (A1)	7.52	Burning wood in house manufactory (A3)	9.95	Production waste of house manufactory (A3)	3.55
PU foam (A1)	6.75	Electricity demand of pre-fabrication in house manufactory (A3)	6.34	Others	2.77
Fasteners (A1)	5.44	Fasteners (A1)	5.56		
Production waste of house manufactory (A3)	5.24	Gypsum boards (A1)	3.31		
Gypsum boards (A1)	4.54	Product package (A3)	2.26		
Mortar (A1)	3.97	Others	11.71		
Burning wood in house manufactory (A3)	3.22				
Others	8.27				

impact originates from the energy intensive manufacturing process. Substituting the mineral wool by wood fiber insulation leads to another GWP-reduction of 3.8%. The ADPe is dominated by gypsum boards (33.19%) (Tables 5, 7). An environmentally friendly alternative to gypsum boards with a very low abiotic depletion potential are straw panels. However, the largest obstacles for an increased use of renewable building materials are still the costs. Ecological aspects might shift to the background when private citizen get into debt for financing a home.

On average the building elements are transported 350 km from house manufactory to the construction site. This contributes 10% of the total GWP and even 20% of the total eutrophication potential (EP). Keeping the transport distance low by choosing a house manufacturer nearby can therefore reduce the environmental burdens drastically.

5 Conclusion

The study provides average LCA data for wood-based wall, ceiling and roof elements and for a prefabricated timber house according to EN 15804 and EN 15978. A data collection within 12 companies which produce prefabricated houses at large scale ensured that the results are representative for the German prefabrication sector. The GWP results are of the same order of magnitude as GWP results from previous case studies which are also in line with the state-of-the-art European standards on sustainable construction works. The highest share of the environmental impacts in the product and construction stages (module A1–A5) of a single- and double-family house is caused by the manufacturing of the building materials (A1). However, with altogether up to 41% of the environmental impact, the prefabrication of the building elements (module A3), the transport of the building elements to construction site (A4) and the processes at the construction site (A5) cannot be neglected. Especially the transport of the building elements (A4) has a high impact (up to 20%). This is reasoned by the bulkiness of the building elements and the fact that many lorries drive back empty from the construction site. From an environmental point of view it is highly recommended to choose a house manufacturer located close to construction site. Further, it is strongly recommended accounting for the prefabrication processes within the product stage (module A1–A3) of EN 15804. Due to the continuously increasing degree of prefabrication, the distinction between processes of manufacturing and processes actually belonging to the construction site seems to be difficult. By taking into account all prefabrication steps carried out in the factory within module A3, the line between product stage (A3) and construction stage (A4-5) remains at the factory gate, as it is regulated by EN 15804.

References

Achenbach H, Rüter S (2016) Ökobilanz-Daten für die Erstellung von Fertighäusern in Holzbauweise (LCA-data for the manufacturing of pre-fabricated timber houses) (In German). Thünen Report 38. J. H. v. Thünen-Institut

CEN (2010) Sustainability of construction works—sustainability assessment of buildings—part 1: General framework, EN 15643-1:2010-12

CEN (2011a). Sustainability of construction works—assessment of buildings—part 2: framework for the assessment of environmental performance, EN 15643-2:2011-05

CEN (2011b) Sustainability of constructions—environmental product declarations—core rules for the product category of construction products, EN 15978:2011

CEN (2012a) Sustainability of construction works—assessment of buildings—part 3: framework for the assessment of social performance, EN 15643-3:2012-04

CEN (2012b) Sustainability of construction works—assessment of buildings—part 4: framework for the assessment of economic performance, EN 15643-4:2012-04

CEN (2013) Sustainability of construction works—environmental product declarations—core rules for the product category of construction products. European Standard EN 15804:2012 + A1:2013. European Committee for Standardization, Brussels

CEN (2014) Round and sawn timber—environmental product declarations—product category rules for wood and wood-based products for use in construction. European Standard EN 16485. European Committee for Standardization

Diederichs SK (2014a) 2010 Status quo for life-cycle inventory and environmental impact assessment of wood-based panel products in Germany. Wood Fiber Sci 46(3):1–16

Diederichs SK (2014b) 2010 Status quo for life-cycle inventory and environmental impact assessment of the core sawmill products in Germany. Wood Fiber Sci 46(1):1–20

ecoinvent Center (2010) ecoinvent Database v2.2. St. Gallen

Fritzen K (2014) Holzrahmenbau–Bewährtes Hausbau System (Timber frame constructions) (In German). In: Fritzen K (ed), vol 5, ISBN/EAN: 9783871042010$4 552

Guardigli L, Monari F, Bradagin MA (2011) Assessing environmental impact of green buildings through LCA methods: a comparison between reinforced concrete and wood structures in the European context. Proc Eng 21:1199–1206

Guinée JB, Gorrée M, Heijungs R et al (2002) Handbook on life cycle assessment. Operational guide to the ISO standards. 1: LCA in perspective. 2a: Guide. 2b: Operational annex. 3: Scientific background. Kluwer Academic, Boston

Gustavsson L, Joelsson A, Sathre R (2010) Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy Build 42: 230–242.

IBU (2012) Umweltproduktdeklaration für das Varitrans Raumtrennsystem, Variante Vollelement-Institut Bauen und Umwelt (Environmental product declaration according to ISO 14025 and EN 15804. Partititon system Varitrans, Fullwall Element) (In German). Editor Institute for building and environment e. V (IBU), owner of the declaration: Dorma Hüppe Raumtrennsysteme GmbH + Co. KG

IBU (2013a) Umwelt-Produktdeklaration nach ISO 14025 und EN 15804. Innentüren aus Holz und Holzwerkstoffen (Environmental product declaration according to ISO 14025 and EN 15804. Interior doors from wood and enginereed wood)(In German). Editor Institute for building and environment e. V (IBU), owner of the declaration: Hüppe Raumtrennsysteme GmbH + Co. KG.

IBU (2013b) Umweltproduktdeklaration für Nichttragende Trennwände aus Gips-Wandbauplatten (Environmental product declaration according to ISO 14025 and EN 15804. Non load bearing partition walls from gypsum) (In German). Institute for building and environment e. V (IBU), owner of the declaration, Bundesverband der Gipsindustrie

IBU (2014) Umweltproduktdeklaration für Kunststofffenster aus PVC-U (Environmental product declaration according to ISO 14025 and EN 15804. Plastic windows from PVC-U) (In German). Institute for building and environment e. V (IBU), owner of the declaration, QKE e.V

IBU (2015) Umweltproduktdeklaration für Spannbeton-Fertigteildecken - Institut Bauen und Umwelt (Environmental product declaration according to ISO 14025 and EN 15804. Prefabricated ceilings from pre-stressed concrete) (In German). Editor Institute for building and environment e. V (IBU), owner of the declaration, DW Systembau GmbH

IPCC (2006) IPCC guidelines for greenhouse gas inventories. Agriculture, forestry and other land use. Chap. 12: harvested wood products, - vol 4. IPCC National Greenhouse Gas Inventories Programme, Paris, p. 4

ISO (2006a) Environmental labels and declarations—type III environmental declarations—principles and procedures. International Standard ISO 14025. International Organization for Standardization, Geneva

ISO (2006b) Environmental management—life cycle assessment—principles and framework (ISO 14040:2006). p. 44

ISO (2006c) Environmental management—Life cycle assessment—requirements and guidelines (ISO 14040:2006), p. 84

König H, de Cristofaro L (2012) Benchmarks for life cycle costs and life cycle assessment of residential buildings. Build Res Inf 40(5):558–580

Monteiro H, Freire F (2012) Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods. Energy Build 47:572–583

PE International (2014) GaBi 4 software and GaBi professional database version 4.108. PE International, Leinfelden-Echterdingen

Penaloza D, Norén J, Eriksson PE (2013) Life cycle assessment of different building systems: the Wälludden case study—technical Research Institute of Sweden, p. 58

Peuportier BLP (2001) Life Cycle Assessment applied to the comparative evaluation of single family houses in the french context. Energy Build 33:443–450

Rüter S, Diederichs SK (2012) Ökobilanz-Basisdaten für Bauprodukte aus Holz (ÖkoHolzBauDat) (LCA Data for building products from wood (ÖkoHolzBaudat)). In: (In German). Final report. Johann

Heinrich von Thünen-Institute, Institute for wood technology and wood biology, Hamburg

Rüter S (2013) Der Umweltbeitrag der Holznutzung. In: ed Cheret P et al Urbaner Holzbau. Chancen und Potenziale für die Stadt (The environmental performance of the use of wood. Urban wooden constructions. Possibilities and potentials in citys) (In German). DOM, Berlin (German)

Scharai-Rad M, Welling J (2002) Environmental and energy balances of wood products and substitutes. Rome, University of Hamburg and Federal Research Centre for Forestry and Forest Products. Food and Agriculture Organization of the United Nations, p 63

StBa (2010) Ausgewählte Zahlen für die Bauwirtschaft, 07/2010 (Seclected numbers of the construction industry, 07/2010) (In German). Federal statistical office of Germany, Wiesbaden

StBA (2013) Bautätigkeit und Wohnungen (Construction activity and living) (In German). Federal statistical office of Germany, Wiesbaden

Takano O, Hafner A, Linkosalmi L, Ott S, Hughes M, Winter S (2015) Life cycle assessment of wood construction according to the normative standards. Eur J Wood Prod 73(3):299–312

Wenker JL, Achenbach H, Diederichs SK, Rüter S (2016) Life cycle assessment of wooden interior doors in Germany—a sector representative approach for a complex wooden product according to EN 15804 methodology. J Ind Ecol 20 (4): 730–742