Building and Environment 79 (2014) 20–30

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Comparison of life cycle assessment databases: A case study on building assessment

Atsushi Takano [a,*], Stefan Winter [b], Mark Hughes [a], Lauri Linkosalmi [a]

[a] Department of Forest Products Technology, School of Chemical Technology, Aalto University, Tekniikantie 3, 02150 Espoo, Finland
[b] Chair for Timber Structures and Building Construction, Technical University of Munich, Arcisstraße 21, 80333 München, Germany

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form
23 April 2014
Accepted 25 April 2014
Available online 9 May 2014

Keywords:
Life cycle assessment (LCA)
LCA databases
Greenhouse gas emission
Building
Cradle-to-gate
Open information

ABSTRACT

Comparability of life cycle assessment (LCA) results based on different background data has long been debated. This is one of the main issues in building LCAs since buildings are complex products, which require multiple material data for the assessment. The objective of this study was to investigate numerical and methodological differences in existing databases related to building LCAs. The five databases selected were compared in terms of greenhouse gas (GHG) emission values in the material production phase of the three reference buildings, two wooden buildings with different frame types and a precast concrete framed building.

The results demonstrated that the databases show similar trends in the assessment results and the same order of magnitude differences between the reference buildings are shown by all the databases. It was also revealed that the numerical differences between the databases are quite large at some points and the differences originate from multiple data elements. The findings indicate the importance of the number of data and a clear statement of the bases of the values for comparative assessment. It would be more realistic to develop a reporting and communication system for LCAs rather than trying to unify the methodologies among the databases. An optimization of open information is significant for further development of LCA databases.

1. Introduction

In recent years, the desire to quantifying the environmental impact of human activities has increased more and more in order to help mitigate climate change. Various environmental certification systems are being established such as the Environmental Product Declaration (EPD) [1] and thanks to this trend, the quantifiable impact, such as carbon footprint or energy demand can, for instance, be seen on a product's label and in advertisements in daily life. This raises our awareness about environmental problems and leads competition in industry. Environmental life cycle assessment (LCA), which is a tool for assessing the environmental impact of products and services over their life cycles has been standardized and is now widely used. LCA supports industry or policymaker in making reasonable decisions concerning products, processes and policy strategies. Since LCA is a data-intensive method, the availability of adequate and reliable data is a fundamental issue for the assessment [2]. Normally it is not easy for LCA practitioners to access all primary data due to confidentiality and thus a number of diverse databases have been developed internationally to satisfy the demand for LCAs [3].

However the direct comparison of databases is debatable, because they consist of data collected from various sources and are based on different calculation methodologies according to their purpose. In principle, there are two different basic approaches to LCA, a process-based approach and an economic input–output (EIO) based approach. The process-based approach is the original method of LCA that computes the environmental input and output as it follows the actual process flow, whilst the EIO method is an inter-industry economic input–output analysis based on monetary transactions and resource consumption data [4,5]. Several researchers have conducted a comparison of LCA databases modelled by the two different approaches [6–8] and the results commonly indicate fundamental gaps in the modelling of data, which sometimes results in significant difference in the assessment result. But it has also been found that most of the values from the two approaches were the same order of magnitude [8]. Recently a hybrid method combining both approaches has been proposed and developed into a new LCA model [9].

* Corresponding author. Tel.: +358 (0)503442098; fax: +358 (0)98554776.
E-mail address: atsushi.takano@aalto.fi (A. Takano).

http://dx.doi.org/10.1016/j.buildenv.2014.04.025
0360-1323/

Peereboom et al. [2] conducted a comparison of six widely used European life cycle inventory (LCI) datasets to identify the data elements that accounted for major differences, and observed the influence of those elements on the result of an LCA conducted on the production of polyvinyl chloride. The main finding of Peereboom et al.'s research was that the specific data elements causing major numerical differences in the LCA results were geographical and temporal factors, technological representativeness, system boundaries, allocation methods and different category definitions for the inventories. The result indicated that different datasets would lead to different conclusions even in LCA studies on the same product. Therefore the authors recommended an appropriate and explicit description for the dataset, regular updating and high transparency and reliability of the dataset.

Chomkhamsri and Pelletierv [10] analysed methodological issues in existing environmental footprint standards and concluded that some important LCA modelling aspects are still inconsistent across the standards for product-related assessment. Reap et al. [11,12] specified methodological problems in LCAs based on a literature survey. In addition, Frischknecht [3] discussed the possibility of a set regional and global LCA databases based on the analysis of the currently used methodologies. The author concluded that one single ideal background database would not be realistic, and plurality in LCA with harmonization of some possible methodological aspects was recommended.

LCA has been also applied to the construction industry and much research has been done from several perspectives to understand the environmental profile of buildings and to investigate solutions to mitigate the impact over a building's life cycle [13–18]. However, comparability of results is also one of the main issues in building LCAs today [19]. Yokoo et al. [20] demonstrated the numerical differences in building LCA results arising from different database use. The numerical differences were shown clearly, although the number of building materials studied was limited and the reasons for the differences were not discussed. With this background, the objective of this study was to investigate numerical and methodological differences in existing databases related to building LCAs. Buildings are complex products consisting of many materials, so that appropriate LCA data for building materials is a prerequisite for the assessment. Thus building LCAs might be more sensitive to background data selection. Although little scientific attention has been paid to this question so far, it is important for comparable environmental assessment in practice.

Five LCA databases were compared by calculating greenhouse gas (GHG) emission values with their datasets in the material production phase (Cradle-to-gate) of three reference buildings. Numerical differences in the building assessment results arising from the different databases used were observed and reasons for the variations were investigated from the database's methodological background point of view. In addition, possible opportunities for the further development of LCA databases and the communication of assessment results are discussed from a practical perspective.

2. Materials and methods

2.1. Reference buildings

Three small box-shaped buildings ('box buildings') constructed at Otaniemi (Finland) were used as the reference buildings. The three box buildings had the same interior floor-area (10.14 m^2) and the same U-values (Wall and Floor = 0.1 $W/m^2 K$ Roof = 0.09 W/m^2K). The first building, which was of light-weight timber construction ('Light weight box'), consisted of walls, floor, and roof elements framed with I-joists and LVL. The second building was of massive timber construction ('Massive box') and composed of cross-laminated timber (CLT) logs, forming the structural frame, and additional non-load bearing insulation elements framed with I-joists and LVL. The third building consisted of a precast concrete panel structure ('PC box'). Fig. 1 shows the basic composition of the buildings. These buildings were selected for the case study for the following reasons: 1) all detail information of the buildings was available, 2) the scale of the buildings was reasonable for the purpose of this study, 3) the buildings include the main construction materials, such as concrete, steel and several wood products, that suit the purpose of this study.

The volumes of the building components were converted to mass for the LCA calculations using the density of the materials. The total mass of each component used in the buildings are summarised in Table 1. Building service equipment, interior finishing, window and door were excluded from the calculation because they were the same in all buildings.

2.2. Compared life cycle assessment databases

The five databases compared in this study were: 'GaBi' (GaBi 6 professional and construction database), 'ecoinvent' (ecoinvent database V3.0), 'IBO' (the reference database published by the Austrian Institute for Healthy and Ecological Building GmbH), 'CFP' (the database for the carbon footprint of products Japan) and 'Synergia' (the datasets in SYNERGIA carbon footprint calculation tool developed by the Finnish Environment Institute) [21–25]. At the time the research was carried out, the latest versions of all the databases were used. GaBi and ecoinvent are commercial LCI databases, whilst IBO, CFP and Synergia are national open databases showing life cycle impact assessment (LCIA) results (CFP and Synergia show only GHG emission values) for the production phase of products. Brief descriptions of each of the databases are given below, whilst basic information about each is summarised in Table 2.

2.2.1. GaBi

The GaBi database is the largest internally consistent LCA database developed by PE international GmbH, Germany. The aim of this database is to provide unique and up-to-date life-cycle inventory (LCI) information to commercial users. This database comprises internationally collected primary LCI datasets from industry, associations and the public sector. The database is regularly updated based on industry resources, scientific knowledge, technical literature and internal patent information. The GaBi database is used as a reference database in Ökobau.dat, which forms the basis for the calculation of building LCAs in the context of the DGNB: German building certification system [26,27].

2.2.2. ecoinvent

The ecoinvent project was launched in late 2000 through a cooperation of several Swiss federal offices and research institutes of the ETH domain (Swiss Federal Institutes of Technology). The first database (version 1.01) was published in 2003 and the second version (v2.0) was released in 2007 based on an extension and revision of the first database. The latest version (v3.0) was released in May 2013. The aim of the ecoinvent project was to harmonize and update several public LCA databases developed by different institutes in Switzerland. In order to respond to increasing attention and the needs of LCA as well as demand for a high quality, reliable and consistent LCI, data has been collected over different industrial sectors. The ecoinvent database is one of the most well-known LCI databases worldwide [28,29].

2.2.3. IBO

The aim of the IBO database is to display the environmental performance of building materials and to help the development of

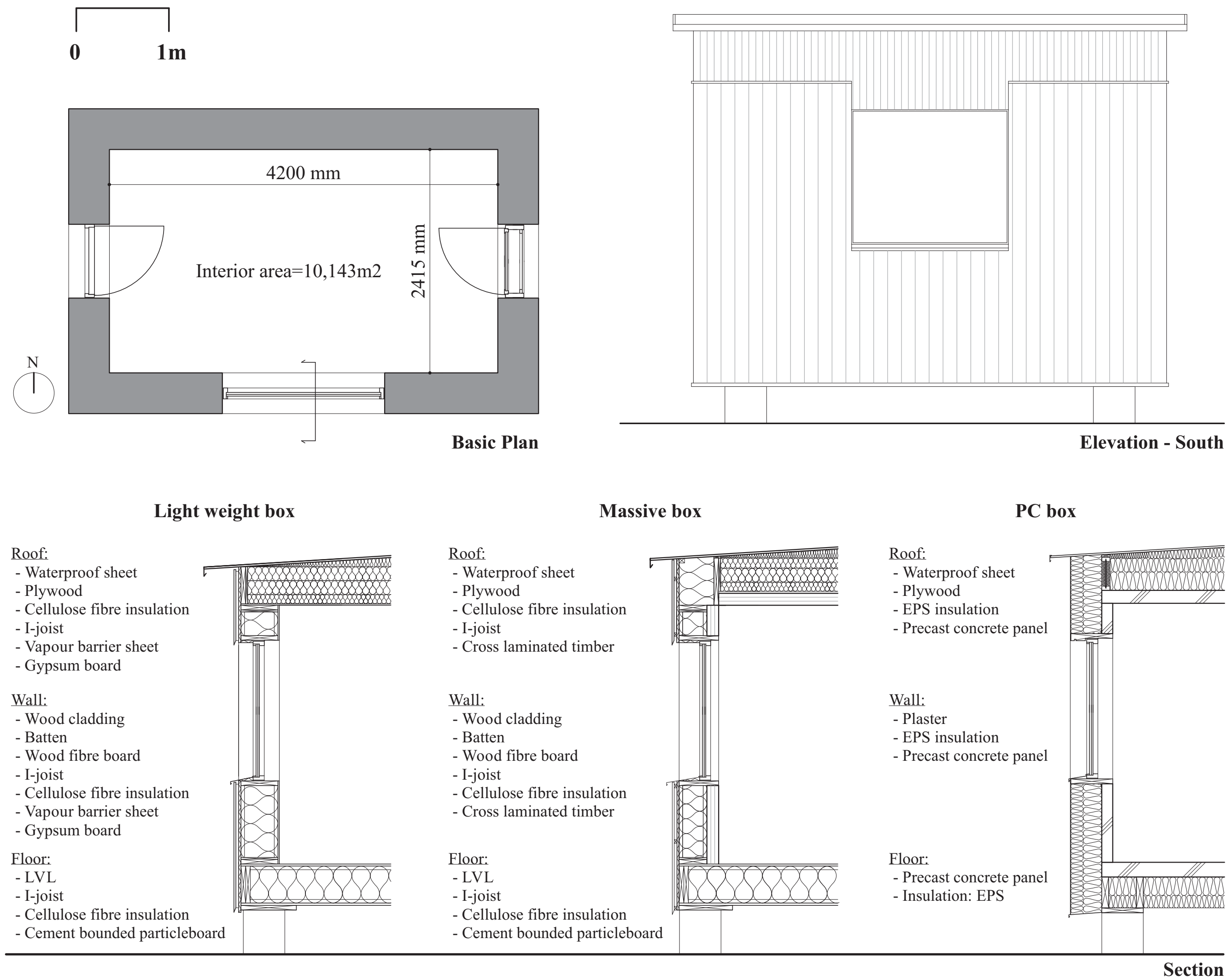


Fig. 1. Basic plan, elevation and detail section of the box buildings.

Table 1
Total mass and density of each building component.

	Density (kg/m3)	Moisture contents (%)	Used mass (kg)		
			Light weight	Massive	PC
LVL	510	10	2194	2036	813
Cross laminated timber (Spruce)	470	12	0	3125	0
OSB	615	–	210	196	61
Cement bonded particleboard	1000	–	428	457	0
Plywood	450	9	201	480	194
Sawn timber (Spruce)	482	12	1114	1055	0
Wood cladding (Pine board)	549	12	504	544	0
Wood fibre board	300	–	576	681	0
Concrete	2400	–	0	0	18,373
Galvanised steel plate	7850	–	78	82	214
Reinforcing rod	7850	–	0	0	672
Steel fixing	7850	–	28	33	38
Cellulose fibre	40	–	1045	1002	0
EPS	30	–	0	0	971
Plaster	850	–	0	0	281
Gypsum board	930	–	817	0	0
Vapour barrier sheet	–	–	5	0	0
PVC roofing	–	–	43	44	42
Others	–	–	30	2	14

the impact assessment for building material production. The database provides the characterized LCIA values for the production phase of building materials in terms of ‘Global warming potential (GWP)’, ‘Acidification potential’ and ‘non-renewable primary energy demand’. The datasets have been collected from industrial and literature data since 1994 and updated continuously. Austria and its neighbouring countries is the geographical target. The ecoinvent database is used as a background database (i.e. for energy systems, transport systems, etc.) in this database [30].

2.2.4. CFP

The database of the CFP project in Japan is a dataset in terms of GHG emission (carbon footprint) for the cradle-to-gate phase of products. The dataset is modelled on the EIO approach. The aim of this database is to facilitate the carbon footprint calculation of products for industries. CFP is the first EPD system in Japan organized by the cooperation of four ministries. The dataset has been developed under the direction of the National Institute of Advanced Industrial Science and Technology based on the existing national database, literature and statistics [31].

2.2.5. Synergia

SYNERGIA is a carbon footprint calculation tool for the main structure of buildings, developed by the Finnish environmental

Table 2
Overview of the databases.

Name of database/dataset	GaBi	Ecoinvent	IBO	CFP	Synergia
Organiization	PE International	Swiss Centre for Life Cycle Inventories	IBO Austrian Institute for Healthy and Ecological Building GmbH	Japan Environmental Management Association for Industry/Advanced Industrial Science And Technology	Finnish Institute of Environment
Country	Germany	Switzerland	Austria	Japan	Finland
Primary data source	Industrial data Literature data Other database (ELCD[a], IBU[b] etc.)	Industrial data Literature data	Industrial data Literature data Other database (ecoinvent etc.)	Statistic data Literature data	Industrial data Literature data
Type of database	Commercial (LCI)	Commercial (LCI)	Open (LCIA)	Open (LCIA)	Open (LCIA)
Type of data	Process based	Process based	Process based	EIO based	Process based
Number of construction material data	Approx. 600	Approx. 540	334	Approx. 130	54
Aggregation of process and inventory	Specified individually	Specified individually	Aggregated	Aggregated, but inventories are listed	Aggregated
Impact assessment method: GWP 100	CML2001	CML2001	CML2001	IPCC SAR[c]	DAIA[d]
Geographical representativeness	Germany or Europe	Switzerland or Europe	Austria and neighbouring countries	Japan	Finland
Temporal representativeness	Annual average (2005–2011)	Annual average (2000–2007)	Not specified, but recent data is selected	Annual average mainly 2000	Annual average mainly 2000
Technological representativeness	Standard of current used technology	Average of current used technology or Best available technologies	Average of current used technology	Average of current used technology	Average of current used technology
Electricity mix	National/Regional average mix	National/Regional average mix	European/Regional average mix	National average mix	National/Industrial average mix
System boundary	Clearly stated	Clearly stated	Clearly stated	Clearly stated	Clearly stated
Allocation method	Economic value and Physical relation	Economic value and Physical relation	Economic value and Physical relation	Economic value and Physical relation	Economic value and Physical relation

[a] ELCD:European reference Life cycle Database.
[b] IBU: Institut Bauen und Umwelt e.V.
[c] Intergovernmental panel on Climate Change, The Second Assessment Report.
[d] Decision Analysis Impact Assessment.

institute. The tool incorporates a dataset of specific weight and GHG emission values for various building materials (cradle-to-gate phase). The dataset has been prepared by referring to several existing datasets in Finland, mainly based on the national EPD database (RT Environmental Declaration). Since there was inadequate documentation regarding the methodology of the dataset, here the method used by VTT (Technical Research Centre of Finland) was referred to as the background methodology [32–34].

2.2.6. Validity of the comparison

GHG emission values for the cradle-to-gate phase of the reference buildings were calculated with the five databases and numerical differences arising from different databases were observed. Since there is variety in the modelling approach and style between the databases, it would be appropriate to compare the results from a broader aspect, such as the magnitudes of differences between the three reference buildings. It should be meaningful to compare different types of database in order to understand their features. The differences in the results could be discussed by looking at the various data elements of the databases. An outline of data elements of the databases is summarised in Table 2.

2.3. Applied data

Where there was no exact data in the databases, the most similar material data was chosen (e.g. plywood data for LVL). This substitution might have had some effect on the results and this uncertainty would increase in databases with a smaller number of data. This point is discussed in Section 3.3.1. The list of data applied from each database is given in Table 3. GHG emission from biogenic fuel combustion is handled as zero emission in the all databases.

2.4. Statistical analysis

Relative standard deviation (RSD) was calculated to quantify the deviation of the results from the different databases. RSD (Equation (1)) is a normalized measure of dispersion of a probability distribution [35].

$$RSD = \sigma/\mu \tag{1}$$

where RSD is relative standard deviation (%)

σ is standard deviation of the result from the databases (kg CO_2 –eq./m^2)
μ is mean of the result from the databases (kg CO_2 -eq./m^2)

The ecoinvent database was set as the reference database and the percentage of relative differences (PRD) in the result to the other databases were determined using Equation (2). The choice of reference database does not imply a value judgement. This method can indicate a positive or negative difference compared with the reference database and facilitates a comparison as an index. For instance, PRDs of 200%, 100%, 50% and 0% mean that the results from the database is three times as large, twice as large, 1.5 times as large and equally as large as the result from the reference database, respectively. When PRD is negative, for instance −66.6% and −50%, the results from the database are, respectively, one third or one half of the results given by the reference database [2].

Table 3
Applied data name in each database.

	GaBi	Ecoinvent	IBO	CFP	Synergia
OSB	OSB Egger Mix (A1-A3)	Oriented strand board, at plant	OSB panels OSB 3 MUPF/PMDI	High density fibre board	Chipboard
LVL	Laminated veneer lumber	Plywood, indoor use, at plant, u = 20%, hardwood	Laminated Veneer	Special plywood	Standard conifer plywood
Cross laminated timber (Spruce)	Three-Layers laminated wood panel pine	Three layered laminated board, at plant	Three layered laminated board	Glue Laminated timber	Glued laminated timber
Cement bonded particleboard	Wood cement board Duripanel -Eternit	Particleboard, cement bonded, at plant	Chipboard, cement bonded	Particleboard	Chipboard
Plywood	Plywood board	Plywood, indoor use, at plant, $u = 20\%$, hardwood	Plywood, indoor use	Normal plywood	Standard conifer plywood
Sawn timber	Timber spruce MC10,7%	Sawn timber, softwood, raw, kiln dried, $u = 10\%$, at plant	Timber, spruce, rough-sawn, tech, dried	Sawn timber	Sawn timber
Wood cladding	Timber Pine MC10,7%	Sawn timber, softwood, raw, kiln dried, $u = 10\%$, at plant	Timber, spruce, planed, tech, dried	Sawn timber (board)	Sawn timber
Concrete (20/25)	Concrete C20/25	Concrete, normal, at plan	Reinforced Concrete	Concrete	Ready-mixed concrete K35
Wood fibre board	Wood fibre board DFF -Egger	Fibre board soft, at plant	Porous wood fibre board	Insulation board	Fibreboard, softboard
Cellulose fibre	Cellulose fibre blowing insulation material	Cellulose fibre, inclusive blowing in, at plant	Cellulose fibre insulation flakes	Insulation board	Wood fibre insulation from collected paper
EPS	Expanded polystyrene (Ps 20)	Polystyrene foam slab_ at plant	EPS W30 Polystyrene foam insulation, expanded	EPS products	Extrusion-compressed polystyrene
Plaster	Gypsum lime plaster	Base plaster, at plant	Gypsum plaster	Calcined plaster	Lime plaster 50/50
Gypsum board	Gypsum plaster board (Fire protection)	Gypsum plaster board_ at plant	Gypsum plaster board	Calcined plaster	Gypsum board
Filler	Interior plaster (lime-gypsum)	Base plaster, at plant	Gypsum filler mass	Calcined plaster	Average filler
Vapour barrier sheet	PE-HD with PP fleece for sealing	Fleece_ polyethylene_ at plant	Vapour pressure compensation layer	LDPE (Low density polyethylene)	LDPE (Low density polyethylene foil)
Air tight tape	Joint gasket tape, PE/PP film	Polyvinylidenchloride, granulate, at plant	Water stop tape	PVC products	Polypropylene
PVC roofing	PVC roofing membranes	Polyvinylidenchloride, granulate, at plant	PVC sealing sheet	PVC products	Polyethene (HD)
Glass fibre mesh	Glass fibre mesh	Glass fibre_ at plant	Fibre glass reinforcement	Glass fibre (choped strand mat)	Glass wool
Air tight gum (EPDM)	Plastic profile EPDM	Synthetic rubber, at plant	EPDM	EPDM	Polyethene (HD)
Sealing sheet (EPDM)	Plastic profile EPDM	Synthetic rubber, at plant	EPDM	EPDM	Polyethene (HD)
Joist hanger	Steel profile V&M	Steel product manufacturing_ average metal working	Steel, low alloyed	Hot dip galvanized steel	Hot-dip galvanized steel products
Reinforcing rod	Reinforced steel (wire)	Reinforcing steel, at plan	Reinforcing steel	Steel rod	Reinforcement steel
Zincked Metal Plate	Steel sheet	Steel product manufacturing_ average metal working	Steel sheet, zinc coated	Electrolytic zinc-coated steel sheets	Hot-dip galvanized steel products
Steel angle	Steel profile (_I_U_H_L_T_)	Steel product manufacturing_ average metal working	Steel, low alloyed	Steel profile	Steel sections
Steel anchor	Steel profile V&M	Steel product manufacturing_ average metal working	Steel, low alloyed	Steel bolt and nut	Hot-dip galvanized steel products
Staple	Steel profile V&M	Steel product manufacturing_ average metal working	Steel, low alloyed	Screw	Hot-dip galvanized steel products
Screw	Steel profile V&M	Steel product manufacturing_ average metal working	Steel, low alloyed	Screw	Hot-dip galvanized steel products

Note: Substituted material data is highlighted by grey hatch.

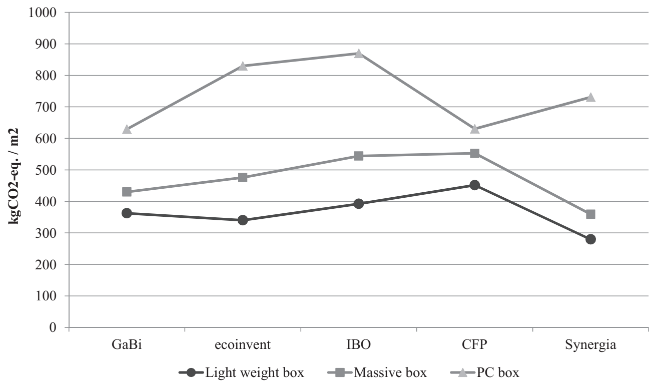


Fig. 2. GHG emission value (Cradle-to-gate) of the three box buildings calculated with the five databases.

$$\mathrm{PRD} = \left(\mathrm{GHG}_x - \mathrm{GHG}_{\mathrm{ref}}\right) / \mathrm{GHG}_{\mathrm{ref}} \times 100 \qquad (2)$$

Where PRD is Percentage relative differences (%)

GHG_x is GHG emission calculated by database x (kg CO_2 -eq.)
$\mathrm{GHG}_{\mathrm{ref}}$ is GHG emission calculated by ecoinvent database (kg CO_2 -eq.)

3. Results and discussion

3.1. Comparison on building assessment results

Fig. 2 shows the GHG emission values for the material production phase of the reference buildings calculated with the five databases. On the whole, the assessment results from the databases seem to be in line with each other. In particular, all databases show the same trend in the GHG emission values, namely that the PC box exhibits the highest value and the light-weight box the lowest. This result is consistent with a previous study [20]. They compared concrete frame and steel frame building with three LCIA databases in terms of primary energy consumption and CO_2 emission during the material production phase of the buildings. Each database naturally showed different numerical results, but the concrete building always exhibited higher value than the steel building.

Additionally, similar differences between the results of the three boxes are found in the case of each database, except for CFP, where the difference between the PC box and the other two is smaller.

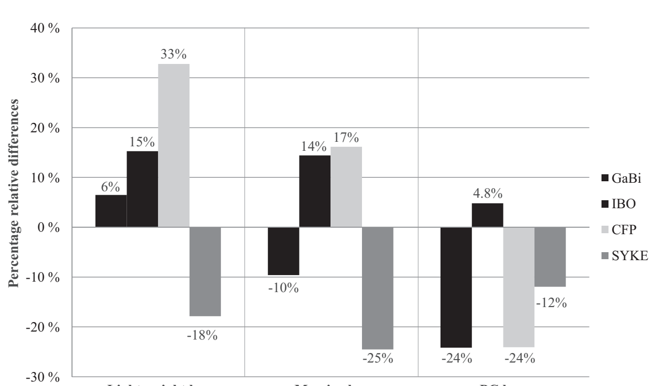


Fig. 3. Percentage relative differences in the assessment results of the reference buildings caused by the different databases (reference database is ecoinvent).

Fig. 3 presents the PRD in the assessment results of the three boxes. The difference between the highest result and the lowest result in Light weight box, Massive box and PC box are 1.6, 1.5 and 1.4 times respectively. In the case of the wooden boxes, CFP yields the highest GHG emission values and Synergia the lowest value at all times. GaBi and ecoinvent show very similar values in the case of the wooden boxes. IBO and ecoinvent yield relatively higher values to the PC box, whilst the other three databases are quite similar.

3.2. Comparison on building component level

In order to see in detail the differences between the databases, the assessment results of the reference buildings are presented according to the main material groups, as shown in Fig. 4. For each material group, the RSD values are also shown in the figure to illustrate the disparity between the databases. In all cases, larger RSD values can be seen in the case of insulation and plastic materials. In addition, the databases show fairly large variation in the metal products of the PC box. On the other hand, the difference is relatively small in the wood products and concrete. Although the largest differences can be found in plastic products, it does not affect the results very much because of the small amounts used. Wood and insulation products are the main GHG emitters in the wooden boxes, and insulation and concrete product are dominant in the PC box.

The effect of differences in the databases on the GHG emission values of the main building materials used was also examined. Fig. 5 displays the PRD of the main materials used in the reference buildings. As shown in the figure, major differences can be found in the values of wood fibre board and cellulose fibre insulation. This is the main reason for the disparity in the results of the wooden boxes. Although the differences in the values of the four main wood products: LVL, CLT, cement bonded particleboard and sawn timber, are relatively small, they also contribute to the differences in the building assessment results because of the large quantities used. On the other hand, the value for concrete does not differ very much between the databases, so that concrete only gives rise to small differences in the results despite the large quantity used. Thus the discrepancy in the results arising from the different databases observed in the PC box originates mainly from variation in the unit value of EPS (Expanded polystyrene) and the reinforcing rods.

3.3. Data elements contributing to the differences

In this section, the reasons for the differences illustrated above are discussed in light of the following data elements: the number of data, LCIA method, technical and geographical representativeness of the material production, temporal and geographical representativeness of the electricity production, system boundary and allocation method, by referring to a previous study [2]. The different LCA approaches, whether it be process-based or EIO-based, is not considered in this study. There should also be an influence of primary data source, accuracy and aggregation level of the data and so on, but these elements are not considered further due to lack of information.

3.3.1. Number of construction material data

As shown in Table 2, there is a large gap between the databases with regard to the amount of construction material data. CFP and Synergia do not include as many data as the other three databases and there is a particular shortage in the case of wood products in both, and in insulation products in the case of CFP. As a result, several building materials had to be calculated with data from similar products as shown in Table 3. This data substitution could

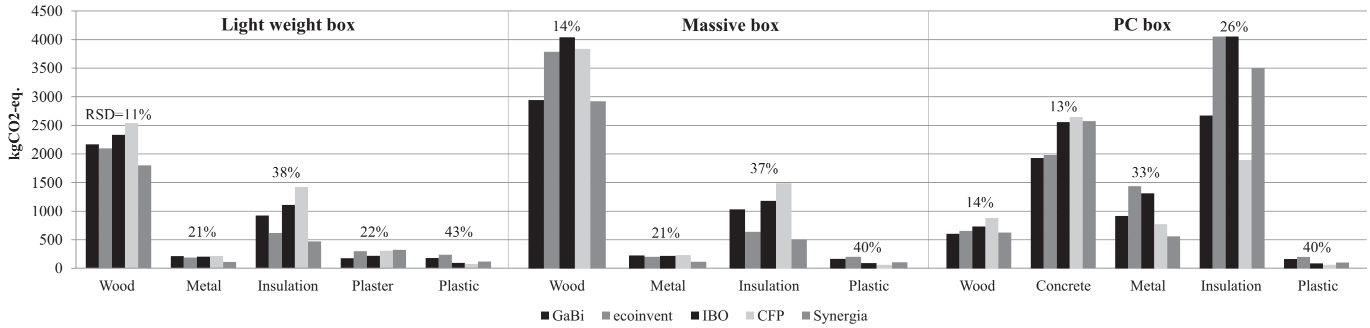
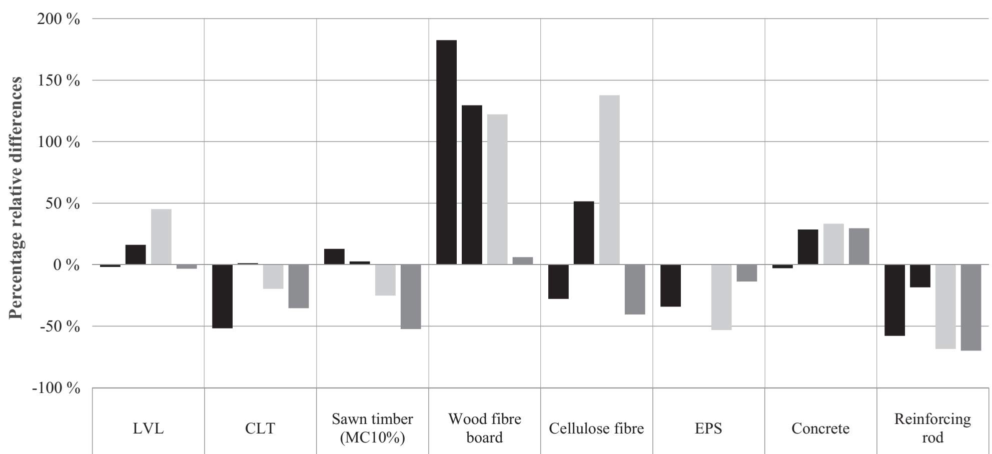


Fig. 4. GHG emission value of material groups in the three box buildings calculated with the five databases, and relative standard deviation of each group.



	LVL	CLT	Sawn timber (MC10%)	Wood fibre board	Cellulose fibre	EPS	Concrete	Reinforcing rod
GaBi	-2 %	-52 %	13 %	183 %	-28 %	-34 %	-3 %	-58 %
IBO	16 %	1 %	3 %	130 %	52 %	0 %	29 %	-18 %
CFP	45 %	-20 %	-25 %	122 %	138 %	-53 %	33 %	-68 %
Synergia	-3 %	-35 %	-52 %	6 %	-41 %	-14 %	30 %	-70 %

GaBi IBO CFP Synergia

Fig. 5. Percentile relative differences in the GHG emission value of main building components shown by the different databases (reference database is ecoinvent).

have a significant influence on the building assessment results. In particular the relatively high GHG emission values obtained using the CFP database in the case of the wooden boxes can mainly be explained by this aspect. Since there was no specific data for wood fibre board and cellulose fibre insulation in the CFP database, data for insulation board was used. This substation would be relevant for wood fibre board, since they are, in general, similar products. On the other hand, the difference arising from the substitution of cellulose fibre is rather critical, since the unit value of insulation board in CFP is much larger than the value of cellulose fibre in the other databases as displayed in Fig. 5.

As a sensitivity analysis, the wooden boxes were recalculated with CFP using the same unit value for cellulose fibre as found in ecoinvent, which seems to be an average value of the all databases. In consequence, the PRD for CFP shown in Fig. 3, decreased from 33% to 17% in the case of the light-weight box and 17%–6% in the massive box, respectively. The substitution of wood products also affects the assessment results to some extent. However, the influence is not critical in this case because of the relatively similar unit value or smaller quantity of the substituted wood products. The substitution obviously lowers the accuracy of the assessment. Nevertheless, this exercise demonstrates that the use of proper data brings the assessment results from the different databases closer. A fundamental requirement for accurate assessment should be to enrich the data in LCA databases.

3.3.2. Life cycle impact assessment method

GHG emission values were calculated with the CML 2001 method (Global Warming Potential) [36] from the LCI data in GaBi and ecoinvent by GaBi software. GHG emission values listed in IBO, CFP and Synergia are based on the CML 2001, IPCC SAR (Intergovernmental Panel on Climate Change, The Second Assessment Report) and DAIA (Decision Analysis Impact Assessment) method, respectively [37,38]. CML 2001 has developed characterization factors based on the IPCC model. In addition, characterization factors for major gasses (e.g. CO_2 and CH_4) determined in the DAIA method is also the same as the CML method. Thus there would be no significant implications, caused by the LCIA method, on the end result in this study. According to a previous study [39], however, different LCIA methods affect LCA results remarkably depending on an impact category, though the influence seems to be small in GWP. Thus impact assessment method used and/or characterization factor should be stated clearly with LCIA results.

3.3.3. Technical and geographical representativeness of the wood products production

As reported in previous studies [2,8], technical and geographical representativeness of material production process seems to be a significant data element. For instance, different technologies led the PRD in the environmental impacts of the PVC (polyvinyl chloride) production process up to −60% [2]. Such major differences in a product data, of course, critically affect building assessment result. Geographical representativeness relates to technical condition of the material production process due to regulations and degree of technological development in each country and region. An influence of technical and geographical representativeness is discussed on the main building materials in Section 3.3.3–3.3.5.

As mentioned before, wood and wood based insulation products dominate the GHG emissions of the two wooden boxes. According to the inventory in the databases, the energy consumption in the wood product manufacturing process is the main factor influencing GHG emission. Land use change also affects the emission, but its contribution is very minor in this case. The energy profile of wood product manufacturing can be divided into two categories, electricity and thermal energy. Electricity is mainly used for machine operations. Thermal energy is used in the drying process (e.g. timber, veneer, and particles) and the pressing process in engineering wood products such as plywood and OSB. In general, the thermal energy for the drying and pressing processes account for approximately 70–90% of total energy consumption during wood product manufacturing [40,41]. Thus the thermal energy resource could be regarded as the main factor influencing GHG emissions in the manufacturing process. Often biomass fuel is used alongside fossil-based fuels to generate this thermal energy, but the ratio between the two naturally varies depending on country, region and mills.

Although the GHG emission values for the wooden construction yielded by GaBi and ecoinvent are similar, the unit values of some wood products differ significantly as shown in Fig. 5. This difference could be explained by looking at the ratio between biofuels and fossil fuels used in the production process. Table 4 presents the ratio of biogenic GHG (GHG emissions from biomass fuel combustion) in the total GHG emission value of wood products in GaBi and ecoinvent. This ratio also includes biogenic GHG emission from electricity consumption in the processes, however, the proportion of biofuel used in electricity generation is very minor in this case (refer Section 3.3.6), so these percentages can be regarded as the ratio of biofuel to fossil fuel used in the production of thermal energy in the processes. Fig. 6 presents the PRD of the wood products between GaBi and ecoinvent. Positive percentage means that the unit value in GaBi is larger than the value in ecoinvent, and negative percentage vice versa. An interesting relationship can be observed when looking at Table 4 and Fig. 6. The GHG emission value in GaBi is lower when the proportion of biogenic GHG emission is higher than in ecoinvent. In other words, different shares of biofuel and fossil fuel in thermal energy generation obviously affect the GHG impact of products, particularly when biogenic GHG emission is taken to be as zero.

The results from Synergia and CFP should be considered from this point as well. In Finland, biofuel accounts for approx. 75% of total fuel consumption in sawmills and approx. 80% of CO_2 emission from the forest industry. In most large sawmills, heat and electricity are generated by their own combined heat and power plants with

Table 4
Ratio of biogenic GHG in the total GHG emission of wood products in GaBi and ecoinvent.

	GaBi	Ecoinvent
OSB	0.20%	49%
LVL	73%	63%
Plywood	70%	63%
Sawn timber	9%	56%
CLT	85%	37%
Wood fibre board	0.10%	48%
Cellulose fibre	34%	23%

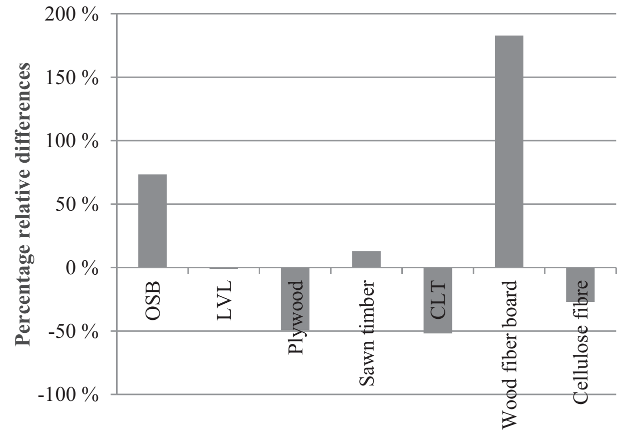


Fig. 6. Percentile relative differences in the GHG emission value of wood products between GaBi and ecoinvent (reference database is ecoinvent).

the wood process residues [42–44]. This accounts for why Synergia, which is based on conditions in Finland, gives a low GHG emission value for the wooden boxes. On the other hand, air-seasoning is still the major drying method in Japan, kiln dried timber accounts for only approx. 20% of the total timber production [45]. For kiln drying, fossil fuel (e.g. heavy oil) is the main thermal energy resource. The datasets in CFP reflects this situation according to the inventory data. Thus it would be reasonable that the unit value of sawn timber in CFP is relatively lower, but the other wood products show slightly higher values than data in the other databases. This would be one reason for the high GHG emission results of wood products calculated with CFP as shown in Fig. 4, although it is difficult to determine this clearly due to the data substitution.

3.3.4. Technical and geographical representativeness of the concrete production

As shown in Fig. 5, the unit GHG emission value of concrete is similar in all the databases. Concrete production can be roughly divided into three processes: aggregates production, cement production and concrete mixing process. According to the inventory in GaBi and ecoinvent, the cement production process is dominant in terms of energy consumption, and the most energy intensive unit process in the production is the firing of clinker. In general, fossil fuels such as coal, petroleum and waste fuel (e.g. used tyre and motor oil) are often used as an energy resource in the firing process [46]. In addition, cement is a material available globally and its production process does not vary [47]. Thus it is possible to say that there should not be too much room for variation in the GHG emissions arising from concrete production because of its unified production system and energy profile. In fact, there is no biofuel used in concrete production according to the inventories of GaBi, ecoinvent and CFP. In other words, an absence of biofuel use in concrete production would cause little difference between the databases.

3.3.5. Technical and geographical representativeness of the expanded polystyrene and reinforcing rod production

The reason why the unit value of the EPS insulation product in CFP is so small compared to the other databases arises from a characteristic of the data. The data in CFP is an average value of all EPS products, which includes not only building insulation products, but also cushioning materials for packing and so forth. Hence the data covers a wide range of technical representativeness, so that the generality of the data is high, but accuracy for the assessment is low.

In the unit value of reinforcing rod, ecoinvent provides much higher GHG emissions data than the other databases, although IBO, which refers ecoinvent as the background database, is close. This point can also mainly be explained by differences in the technical and geographical representativeness of the data. For instance in a comparison between GaBi and ecoinvent, a major difference could be found. The data in GaBi represents the specific situation of steel manufacturing in Germany, whilst the data in ecoinvent represents an average of world and European production. This leads to different data modelling in the furnace system, which affects the GHG impact of steel products significantly. The data in GaBi is modelled using an electric arc furnace (EAF), whilst the data in ecoinvent is modelled on a combination of 37% EAF and 63% basic oxygen furnace (BOF). Since BOF is a much higher energy consumer, resulting in larger GHG emission than EAF, this difference is important. The GHG emission value of the reinforcing rod in ecoinvent becomes about a half, which is more or less the same as the value in GaBi when the data is modelled using 100% EAF.

3.3.6. Temporal and geographical representativeness of the electricity production

The electricity production mix differs depending on time and place. In addition, the reference year for the calculation varies from database to database and data by data. This variation naturally affects the environmental impact of the material production processes. Fig. 7 shows the electricity production mix over six years in the five countries where the databases are mainly represented [48]. The influence of this element could not be verified quantitatively in this study due to lack of information, however, some insights could be gained from the figure. For instance, it is clear that the difference in the geographical representativeness is much more critical than the temporal representativeness, at least over the short time period under consideration. Peereboom et al. [2] demonstrated that the PRD in the environmental impacts caused by different geographical representativeness of the electricity production data were approximately −30 to +50%, whilst different temporal representativeness yielded the PRD of less than 5%. Although electricity is not a major energy source in construction material production in many cases, minor differences between the databases would originate from this point. Clear description of energy mix used and constant update of the data should be important.

3.3.7. System boundary

In general, data handled in this study covers the manufacturing processes of products (Cradle-to-gate phase) and its system boundary is stated clearly. However there is an exception. The transportation process regarding the import of logs is not included in CFP, because of a lack of data. Imported wood accounts for approximately 75% of annual wood consumption in Japan [45]. Thus this data gap would affect the GHG emission value of wood product to some extent, and could be one of the reasons for the low unit value of sawn timber in CFP. As shown in a previous study [6], lack of single production process in the calculation may bring significant difference in the end result. Unification of the system boundary is definitely a precondition for comparability in LCA studies. Moreover, a clear statement of the boundary helps proper interpretation of LCA result, even if certain processes are excluded from the assessment.

3.3.8. Allocation

According to the guideline of the databases, basic allocation rules (physical basis, economic value or other) are similar between the databases. Thus, in principle, this element does not seem to significantly affect the results in this study. However, since how allocation was performed is not often explicitly stated, this issue could not be verified in detail. For all that, the allocation method has long been debated as a critical methodological issue. It is definitely an important issue especially for a system in which multi-output processes or recycling processes possibly occur, like in wood products. Jungmeier et al. [49] reported that economic value based allocation gave approximately 10% higher CO_2 emission value for the sawn timber production than volume based allocation. Moreover, Peereboom et al. [2] showed that economic value based allocation brought the PRD in the environmental impact of the

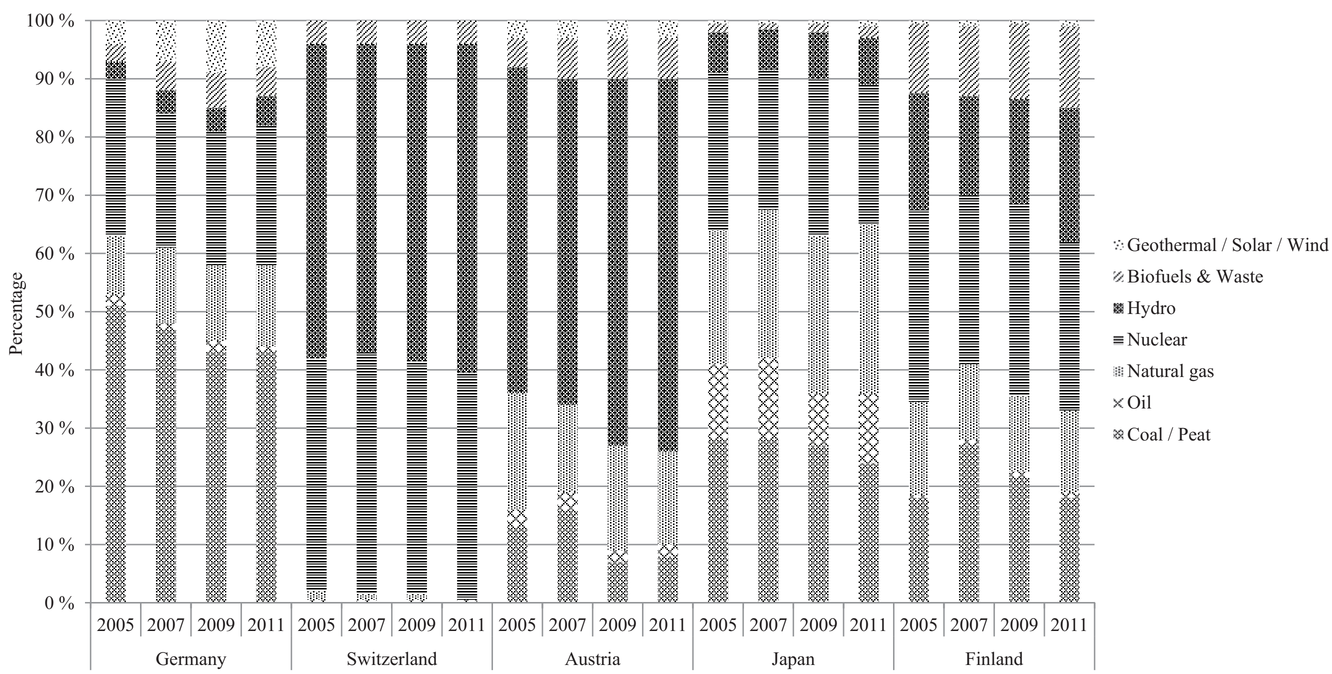


Fig. 7. Electricity production mix in five countries, to where the databases mainly represent, over six years (2005, 2007, 2009 and 2011) [43].

chlorine production up to −18% compared to mass based allocation. As described in the ISO standard 14041 [50], allocation is the third method for dealing with a multi-output process and it is, in principle, a case dependent issue. Thus it may be difficult to unify the method among LCA databases, but a clear statement of the method for the data user is fundamental.

4. Conclusions

Comparability of LCA results based on different background data is one of the main issues in building LCAs since buildings are complex products, which require multiple material data for the assessment. In order to investigate this question, five LCA databases were compared by conducting LCAs for the Cradle-to-gate phase of three reference buildings.

This study demonstrated that the databases show similar trends in the assessment results and the same order of magnitude differences between the three buildings are shown by the all databases. The results also revealed that the numerical differences between the databases are quite large at some points and the differences originate from multiple data elements.

The findings lead to the following general conclusions to further develop LCA databases:

- To enrich the number of data
- Transparent indication of the bases of the values used

Since it stands to reason that there should be the numerical differences in the databases because of a large number of data elements, it seems to be more realistic to develop reporting and communication systems for LCA result rather than in trying to unifying the methodologies among the databases. From a designer's point of view, simpler information would be preferable. In addition, the standard EN15978 describes the simplification of the assessment result of a building [51]. But as demonstrated in this study, the bases of the values need to be known in order to avoid a misreading of the results. In product data, the rule defined by the EPD system would be a relevant format. According to the standard EN15804 [52], it is a requirement to declare information regarding the use of resources based on the LCI with LCIA result. In addition to that, it would be more understandable to indicate the distribution of energy resources along with the production process. Transparency of the data may affect the production process in reality and bring LCA databases close to each other numerically.

With regard to the first bullet point, the development of a national open database would be required. Since adequate information is still lacking in many countries, commercial databases such as GaBi and ecoinvent are often used and developed appropriately. But simple national open data would be very helpful especially for practical users (e.g. architects or constructors) because of its user-friendliness and locality. They do not necessarily need to be an LCI dataset, but LCIA information of products with proper description, as discussed before, would be relevant. For instance, IBO provides a relatively large number of data, but the bases are not explicitly stated. On the other hand, CFP includes few construction material data, but detailed background information is attached to each data. These two points should be compatible. Simple and transparent generic databases will lead to further popularization of LCAs at a practical level.

The findings of the current study are subject to the limitation of sample size. In addition, only GHG emission value for the Cradle-to-gate phase of the buildings was discussed in this study. Thus future research could include other LCA databases, life cycle stages and environmental impact.

Acknowledgements

The authors gratefully acknowledge funding support from CEI-Bois, Finnish Wood Research Oy and the KONE Foundation (44-8215), as well as the assistance of all concerned.

References

[1] Environmental product declaration. Available online at: <http://www.environdec.com/>; May 11, 2013.
[2] Peeredoom EC, Kleijn R, Lemkowitz S, Lundie S. Influence of inventory data sets on lice-cycle assessment results: a case study on PVC. J Ind Ecol 1999;2(3):109–47. http://dx.doi.org/10.1162/jiec.1998.2.3.109.
[3] Frischknecht R. Notions on the design and use of an ideal regional or global LCA database. Int J LCA 2006;11:40–8. http://dx.doi.org/10.1065/lca2006.04.010.
[4] Leontief WW. Quantitative input and output relations in the economic systems of the United States. Rev Econ Stat 1936;18(3):105–25.
[5] Lave L, Cobas FC, Hendrickson C, McMicheal F. Using input-output analysis to estimate economy wide discharges. Environ Sci Technol 1995;29:420–6. http://dx.doi.org/10.1021/es00009a003.
[6] Shelie A, Miller, Thomas LT. Comparison of life-cycle inventory databases – a case study using soy bean production. J Ind Ecol 2006;10:133–47. http://dx.doi.org/10.1162/108819806775545358.
[7] Mongelli I, Suh S, Huppes G. A structure comparison of two approaches to LCA inventory data, base on the MIET and ETH databases. Int J LCA 2005;10(5):317–24. http://dx.doi.org/10.1065/lca2004.12.198.
[8] Hendrickson CT, Horvath Arpad, Joshi S, Klausner M, Lave LB, McMichael FC. Comparing two life cycle assessment approaches: a process model- vs. econ input-output based assessment; 1997. pp. 176–81. http://dx.doi.org/10.1109/ISEE.1997.605313. IEEE 0-7803-3808-1.
[9] Bilec M, Rise R, Matthews H, Sharrard AL. Example of a hybrid life-cycle assessment of construction processes. J Infrastruct Syst; December 2006: 207–15. http://dx.doi.org/10.1061/(ASCE)1076-0342(2006)12:4(207).
[10] Chomkhamsri K, Pelletier N. Analysis of existing environmental footprint methodologies for products and organizations: recommendations, rationale, and alignment. European Commission Joint Research Centre, Institute for Environment and Sustainability (IES); 2011. Available online at: <http://ec.europa.eu/environment/eussd/pdf/Deliverable.pdf>.
[11] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment, part 1: goal and scope and inventory analysis. Int J LCA 2008;13:290–300. http://dx.doi.org/10.1007/s11367-008-0008-x.
[12] Reap J, Roman F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment, part 2: impact assessment and interpretation. Int J LCA 2008;13:374–88. http://dx.doi.org/10.1007/s11367-008-0009-9.
[13] Gustavsson L, Joelsson A, Sathre R. Life cycle primary energy use and carbon emission of an eight-story wood-framed apartment building. Energy Build 2010;42(2):230–42. http://dx.doi.org/10.1016/j.enbuild.2009.08.018.
[14] Jönsson A. Tools and methods for environmental assessment of building products. Methodological analysis of six selected approaches. Build Environ 2000;35(3):223–38. http://dx.doi.org/10.1016/S0360-1323(99)00016-5.
[15] Scheuer C, Keoleian GA, Reppe P. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy Build 2003;35:1049–64. http://dx.doi.org/10.1016/S0378-7788(03)00066-5.
[16] Adalberth K. Energy use during the life cycle of single-unit dwellings: examples. Build Environ 1997;32(4):321–9. http://dx.doi.org/10.1016/S0360-1323(96)00069-8.
[17] Basbagill J, Flager F, Lepech M, Fischer M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Build Environ 2013;60:81–92. http://dx.doi.org/10.1016/j.buildenv.2012.11.009.
[18] Verbeeck G, Hens H. Life cycle inventory of buildings: a contribution analysis. Build Environ 2010;45:964–7. http://dx.doi.org/10.1016/j.buildenv.2009.10.003.
[19] Wittstock B, Fischer M, Böttge J, Gantner J, Ockel E, Braune A. Trends in building & construction life cycle assessment. In: Proceedings of the sustainable buildings – construction products & technologies; 2013. pp. 1004–11. SB13 Graz.
[20] Yokoo N, Terachima T, Oka T. Embodied energy and CO_2 emission associated with building construction by using I/O based data and process based data in Japan. In: Proceedings of the sustainable buildings – construction products & technologies; 2013. pp. 1313–8. SB13 Graz.
[21] GaBi software. GaBi LCA databases. Available online at: <http://gabi-software-databases/>; September 10, 2013.
[22] Ecoinvent center. The ecoinvent database. Available online at: <http://ecoinvent.org/database/>; September 10, 2013.
[23] IBO-Roichtwerte. Available online at: <http://www.ibo.at/de/oekokennzahlen.htm>; September 10, 2013.
[24] JEMAI CFP Program. CFP database. Available online at: <http://www.cfp-japan.jp/calculate/verify/data.html>; September 10, 2013 [Japanese].
[25] SYNERGY carbon footprint tool. Available online at: <http://www.syke.fi/en-US/Research__Development/Consumption_and_production_and_sustainable_use_of_natural_resources/Calculators/Synergy/SYNERGY_Carbon_Footprint_Tool_instructio%2826143%29>; September 10, 2013.

[26] Baitz M, Colodel CM, Kupfer T, Pflieger J, Schuller O, Hassel F, et al. GaBi Database and modeling principles 2012, Version6.0. PE International. Available online at: <http://gabi-6-lci-documentation.gabi-software.com/xml-data/external_docs/GaBiModellingPrinciples.pdf>; November 2012.
[27] König H, Kohler N, Kreibig J, Lutzkendorf T. A life cycle approach to buildings – principles, calculations, design tools. Architektur-Dokumentation GmbH & Co. KG; 2010.
[28] Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, et al. Overview and methodology, data quality guideline for the ecoinvent database version 3. Swiss Center for Life Cycle Inventories; 2013. Available online at: <http://www.ecoinvent.org/fileadmin/documents/en/Data_Quality_Guidelines/01_DataQualityGuideline_v3_Final.pdf>.
[29] Frischknecht R, Jungbluth N. Overview and methodology. Final report ecoinvent v2.0 No.1. Swiss Centre for Life Cycle Inventories; 2007. Available online at: <http://www.ecoinvent.org/fileadmin/documents/en/01_OverviewAndMethodology.pdf>.
[30] Boogman P, Mötzl H. IBO-Richtwerte für Baumaterialien, Wesentliche methodische Annahmen. IBO-Österreichisches Institut für bauen und Ökologie GmbH; 2012. Available online at: <http://www.ibo.at/documents/LCA_Methode_Richtwerte_kurz_120620.pdf>.
[31] JEMAI carbon footprint of products, detail information and process data. Japan Environmental Management Association for Industry; September 10, 2013. Available online at: <http://www.cfp-japan/>.
[32] Nissinen A, Rintala T. Material efficiency and carbon footprint, source data and result forms for carbon footprints: synergy building. SYKE and Pöyry Building Services Oy; 2010. Available onsite at: <http://www.syke.fi/en-US/Research__Development/Consumption_and_production_and_sustainable_use_of_natural_resources/Calculators/Synergy/SYNERGY_Carbon_Footprint_Tool_instructio%2826143%29>.
[33] Rakennustieto environmental declarations. Available online at: <http://www.rts.fi/ymparistoseloste/index_RTED.htm>; September 10, 2013.
[34] Häkkinen T, Tattari K, Vares S, Laitinen A, Hyvärinen J. Methodology for compiling environmental declarations for building products and assessing environmental impacts of buildings. Technical research center of Finland; September 10, 2013. Available online at: <http://virtual.vtt.fi/virtual/proj6/environ/eka-report-2006.pdf>.
[35] Koopmans LH, Owen DB, Rosenblatt JI. Confidence intervals for the coefficient of variation for the normal and log normal distributions. Biometrika 1964;51(1/2):25–32.
[36] Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Hischier R, et al. Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No.3. Swiss centre for Life Cycle Inventories; 2007. Available online at: <http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf>.
[37] Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K. The science of climate change, contribution of WG1 to the second assessment report of the international panel on climate change. Cambridge: Cambridge University Press; 1996. Available online at: https://www.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf.
[38] Seppälä J, Basson L, Norris GA. Decision analysis frameworks for life-cycle impact assessment. J Ind Ecol 2002;5(4):45–68. http://dx.doi.org/10.1162/10881980160084033.
[39] Bovea MD, Gallardo A. The influence of impact assessment methods on materials selection for eco-design. Mater Des 2006;27:209–15. http://dx.doi.org/10.1016/j.matdes.2004.10.015.
[40] Tucker SN, Tharumarajah A, May B, England J, Paul K, Hall M, et al. Life cycle inventory of Australian forests and wood products. Report Project No. PNA008–0708. Forest & Wood Products Australia (FWPA); 2009. Available online at:, <http://www.fwpa.com.au>.
[41] Food and Agriculture Organization of the United Nations. Energy conservation in the mechanical forest industries. Available online at: <http://www.fao.org/docrep/T0269E/t0269e04.htm>; October 10, 2013.
[42] Statistical yearbook of forestry. Finnish Forest Research Institute; 2011. Available online at: <http://www.metla.fi/julkaisut/metsatilastollinenvsk/index-en.htm>.
[43] Statistics Finland. Wood fuels are the most significant energy source in manufacturing. Available online at: <http://www.stat.fi/til/tene/2007/tene_2007_2008-11-05_tie_001_en.html>; 2008.
[44] Korhonen J, Wihersaari M, Savolainen I. Industrial ecosystem in the Finnish forest industry: using the material and energy flow model of a forest ecosystem in a forest industry system. Ecol Econ 2001;39:145–61. http://dx.doi.org/10.1016/S0921-8009(01)00204-X.
[45] Ministry of Agriculture, Forestry and Fisheries, Forest Agency. reportAnnual report on Forest and Forestry in Japan. Available online at: <http://www.rinya.maff.go.jp/j/kikaku/hakusyo/21hakusho/pdf/21_e.pdf>; 2009.
[46] U.S. Environmental Protection Agency. Energy trends in selected manufacturing sectors: opportunities and challenges for environmentally preferable energy outcomes. Available online at: <http://www.epa.gov/sectors/pdf/energy/report.pdf>; 2007.
[47] ClimateTechWiki. Energy efficiency and saving in the cement industry. Available online at: <http://climatetechwiki.org>; October 10, 2013.
[48] International Energy Agency. IEA energy statistic. Available online at: <http://www.iea.org/>; March 28, 2012.
[49] Jungmeier G, Werner F, Jarnehammar A, Hohenthal C, Richter K. Allocation in LCA of Wood-based products, experience of cost action E9. Int J LCA 2002;7(6):369–75.
[50] ISO14041: 1998, Environmental management. Life cycle assessment. Goal and scope definition and inventory analysis.
[51] EN15978: 2011, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.
[52] EN15804: 2012, Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products.