A Methodical Approach for Systematic Life Cycle Assessment of Wood-Based Furniture

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Summary

Existing life cycle assessment (LCA) studies for furniture focus on single pieces of furniture and use a *bottom-up approach* based on their bill of materials (BOM) to build up the data inventories. This approach does not ensure completeness regarding material and energy fluxes and representativeness regarding the product portfolio. Integrating material and energy fluxes collected at company level into product LCA (*top-down approach*) over-rides this drawback. This article presents a method for systematic LCA of industrially produced furniture that merges the *top-down approach* and *bottom-up approach*. The developed method assigns data collected at the company level to the different products while, at the same time, considering that wood-based furniture is a complex product. Hence, several classifications to reduce the complexity to a manageable level have been developed. Simultaneously, a systematic calculation routine was established. The practical implementation of the developed method for systematic LCA is carried out in a case study within the German furniture industry. The system boundary was set in accord with the EN 15804 specification *cradle-to-gate-with-options*. The analysis therefore includes the manufacturing phase supplemented by an end-of-life scenario. The case study shows that the manufacturing of semifinished products (especially wood-based panels and metal components) as well as the electric energy demand in furniture manufacturing account for a notable share of the environmental impacts. A sensitivity analysis indicates that up to roughly 10% of the greenhouse gas emissions are not recorded when conducting an LCA based on a BOM instead of applying the developed approach.

Introduction

Wood-based furniture is a very important and omnipresent commodity. In 2013, approximately 103.3 million pieces of furniture were produced in Germany (German Federal Statistical Office 2014; VDM 2014). As Mantau and Bilitewski (2010) assessed, 6.5 million cubic meters m^3 of particleboard were used for the production of furniture in Germany in 2007. These numbers illustrate the importance of the furniture sector and the need for reliable life cycle assessment (LCA) data of furniture.

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Life Cycle Assessment Data for Furniture

Only limited information on the environmental impacts of (wood-based) furniture is available. Office furniture with a rather low share of wooden parts has been assessed within LCA studies (Babarenda Gamage and Boyle 2006; Babarenda Gamage et al. 2008; Dietz 2005; Spitzley et al. 2006). Several studies resulted in environmental product declarations (EPDs) (Arper 2011; HÅG 2008; RH Chairs 2009; Wiesner-Hager 2014; Svenheim Møbelindustri 2015; Scandinavian Business Seating 2014, 2015; Steelcase 2004). Other types of furniture, for instance, wardrobes and chairs, have also been assessed using specific pieces of furniture with their bill of materials (BOM) (Fet and Skaar 2006; Fet et al. 2009; González et al. 2008; González-Garcia et al. 2011, 2012; Iritani et al. 2015; Laemlaksakul and Sangsai 2013; Mirabella et al. 2014; Skaar and Jorgensen 2013; Wenker 2010). A BOM is a product-specific data set that provides information on materials, semifinished products, and other components used.

Within the mentioned studies, the selection of the specific pieces of furniture serving as an example might not be representative of the products manufactured by the particular company. Additionally, these studies cannot ensure completeness of data collection attributed to the assessment of only those selected pieces of furniture on the basis of their respective BOM. A BOM-based LCA does not necessarily account for infrastructural energy demands, such as, for example, heating and electricity for illumination or dust extraction. Additionally, a BOM-based LCA often does not cover production waste and operating resources such as lubricants, cleaning agents, tap water, and sanding paper. Therefore, this approach cannot guarantee the consideration of all relevant material and energy fluxes. In comparison, a study of the British Furniture Industry Research Association (FIRA) (FIRA 2011), providing carbon footprint calculations for different types of furniture, shows a distinguishing feature: The data collection was carried out at company level. Nevertheless, the data calculation to funtional units, in this case, pieces of furniture, was simply implemented through dividing the company data by the number of pieces of furniture produced. Hence, there is a need for LCA data of furniture based on a systematic assessment, taking into account all material and energy fluxes as collected at company level. A methodical approach for the systematic LCA of furniture is still lacking.

With the exception of the latest LCAs serving as a basis for EPDs (Svenheim Møbelindustri 2015; Scandinavian Business Seating 2014, 2015; Eczacıbaşı Building Products 2015), those studies do not follow EN 15804 (CEN 2013). This standard provides accepted and useful instructions for LCA information along the products' life cycle and further specifies International Standard of Organization (ISO) 14040 (ISO 2006a) and ISO 14044 (ISO 2006b). Although originally designed for building products, the EN 15804 standard provides reasonable advice for conducting LCA of furniture as well.

Aim and Objectives

Based on the work of Wenker and Rüter (2015) as well as Wenker (2015), a methodical LCA approach to cope simultaneously with the issues of complexity, completeness, and representativeness at company level is presented. A case study is carried out applying the method in three German furniture companies. This serves as verification of the method´s reliability and performance and, at the same time, generates average LCA data for furniture.

Background

Complexity of Furniture Products

Furniture is complex in three respects. First, materials used in furniture manufacturing are not limited to wood and engineered wood products (EWPs). They additionally cover, for instance, metal (fittings, frames, etc.), plastic materials (adhesive, coatings, varnish, fittings, etc.), textiles and fabrics, leather, glass, mirrors, and resin-bonded mineral materials. Second, pieces of furniture offer various functions. Main functions of furniture are the storage in an enclosed space, storage on a surface area, seating, and bedding. In addition, design aspects could be named as *visual additional function*. Third, the manufacturing process itself is complex. This aspect is described and illustrated separately in a subsequent section.

The Industrial Furniture Manufacturing Process

Furniture manufacturing at industrial scale is technologically sophisticated and, to a great extent, automated. Processes are complex given that machines are usually nested together and plant components form so-called production lines of large dimensions. This causes challenges in determining the energy demand for specific processing steps given that the energy consumption in the furniture industry, at present, is usually only measured in a total value at company level.

The processing of engineered wood products, which, in the furniture industry, means mainly wood-based panels, is quite different from the processing of solid wood, which is usually sawn wood. Figure S1 in the supporting information available on the Journal´s website illustrates the production of furniture from wood-based panels and from sawn wood. In general, the production steps required within a furniture production site depend strongly on the level of prefabrication of the purchased semifinished products.

Bottom-Up and Top-Down Approach for Data Collection and Data Calculation

Generally speaking, there are two ways to collect and calculate data: bottom-up and top-down. Using the *bottom-up approach*, data collection starts from the chosen functional unit, often a specific product. In this case, the BOM serves as a basis for the life cycle inventory (LCI) and is supplemented by information on standard processes. In contrast, a *top-down approach* means that the first step of data collection is

Table 1 Defined functional groups including the respectively declared unit

Function	Functional group	Declared unit	Example
Storage: Providing an enclosed storing space	*Storage furniture (enclosed space)*	1 kg storage furniture (enclosed space)	Wardrobe, sideboard
Storage: Providing a surface for storage	*Storage furniture (surface area)*	1 kg storage furniture (surface area)	Shelf, table
Seating: Providing seats	*Seating furniture*	1 kg seating furniture	Chair, stool
Bedding or lying: Providing places to lie	*Bedroom furniture*	1 kg bedroom furniture	Bed

Note: kg = kilogram.

superordinate to the data collection for a specific product. For applying the *top-down approach*, a certain organizational level forms the basis for data collection. LCA at company level involving all products produced is named organizational LCA (O-LCA) because it assesses the so-called reporting organization, either in its entirety or in parts. Parts of an organization can be, for example, business divisions, brands, regions, companies, or facilities (Hellweg and Milà i Canals 2014; Martínez-Blanco et al. 2015; UNEP 2015). A product LCA with the *top-down approach* requires the assignment of company-level information to the particular products or functional units. The advantage of a top-down approach is thus ensured completeness because all material and energy fluxes at the assessed organizational level are definitely considered. Various literature mentions the top-down approach in the context of LCA based on input and output data of whole industry sectors and names this approach input-output LCA (IO-LCA) (Finnveden et al. 2009; Hendrickson et al. 2006; Weidema 2004). Thereby, IO-LCA at company level exactly fits the newly established term O-LCA. Combinations of a *bottom-up approach* and *top-down approach*, so-called hybrid approaches, can also be observed (Weidema 2004; Finnveden et al. 2009).

Methodical Approach

The basic idea is a hybrid approach of IO-LCA at company level and a product LCA. A combination of a *top-down approach* and a *bottom-up approach* is provided for the data collection and calculation. International standards have been considered in developing the method for systematic LCA of furniture. In particular, these are ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b), which standardize the implementation of an LCA, as well as EN 15804 (CEN 2013) and EN 16485 (CEN 2014), which inter alia include rules for dividing the entire life cycle into defined modules and instructions for handling wood-inherent material properties.

Classification for Complexity Reduction

Several classifications are introduced to aggregate products, materials, and processes in furniture production. The aim of classifying is to reduce the complexity of the empirical system while shifting reality to an LCA model. Therefore, the LCA model does not show the original complexity of the system under study.

Classification by Function (Functional Groups)

Four so-called functional groups were defined with the four main furniture functions identified (table 1).

They serve as primary classes for the further processing of the data collected at company level. Functional groups are launched to respect the concept of the functional unit in the LCA methodology.

The function of pieces of furniture includes very subjective details (*visual additional function*). Additionally, combinations of the main functions, for example, *enclosed space* and *surface area* provided by the same piece of furniture, cannot be expressed by a single number. Because of this, the sum of the functions cannot be quantified. In consequence, it was necessary to use the declared unit as stated in EN 15804. Thus, *1 kilogram (kg) of furniture plus packaging* was defined as a declared unit within each functional group representing virtual average pieces of furniture on a mass basis. The basic idea is that the declared unit *1 kg furniture plus packaging* provides environmental information per kg as an objective basis. Should someone want to compare two specific pieces of furniture, this can be done easily by multiplying the specific product mass with the environmental impacts per kg.

Classification by Materials Used (Material Classes)

Materials with different levels of prefabrication are used to produce furniture. Consequently, different semifinished products require different production processes at the furniture production site itself (level of vertical integration). Thus, the materials used strongly affect the on-site energy consumption. It is thus important to classify the products with respect to the materials used. Material classes allow for the classification of furniture based on the load-bearing material in combination with the surface finish applied (table 2). Empty fields show combinations of load-bearing material and surface finish, which are not common within the furniture industry.

Table 2 Material classes derived from the criteria carrier material and surface finish, modified from Wenker (2010)

		X	Y	Z
	Load-bearing material / *Surface finish*	*Solid wood (SW)*	*Engineered wood products (EWP, wood-based panels)*	*Mixture of solid wood and engineered wood products*
1	Veneer		EWP/veneer **Y1**	SW, EWP/veneer **Z1**
2	Clear varnish	SW/clear varnish **X2**		
3	Colored varnish	SW/colored varnish **X3**	EWP/colored varnish **Y3**	SW, EWP/colored varnish **Z3**
4	Furniture oil/wax	SW/oil, wax **X4**		
5	Plastic/resin coated		EWP/plastic **Y5**	SW, EWP/plastic **Z5**
6	Fabrics/leather/others	SW/fabrics . . . **X6**	EWP/fabrics . . . **Y6**	SW, EWP/fabrics . . . **Z6**

Note: The identification of the material classes is given by combining the headings of columns and rows, for example, "X2."

Table 3 Example for the interaction of product group, material class, and functional group

	Product group 1	*Product group 2*	*Product group 3*	*Product group n*
Name	Wardrobes	Wardrobes	Dining tables	. . .
Material class	Y1 EWP/veneer	Y5 EWP/plastic	Y1 EWP/veneer	. . .
Functional group	Storage furniture (enclosed space)	Storage furniture (enclosed space)	Storage furniture (surface area)	. . .

Note: EWP = engineered wood products.

Combination of Classification by Function and by Materials (Product Groups)

A combination of functional groups and material classes had to be developed for the data calculation. Hence, so-called product groups were additionally created as the highest resolution possible in the presented work. A product group is characterized by a specific material class and, in a second step, is assigned to a functional group. In every case, the primary classification attribute is the function. This means that pieces of furniture made of the same material, but offering a different function, cannot be sorted in the same product group. Table 3 exemplifies the concept of the product groups. The number of assessed product groups is not limited a priori, but is drawn from the portfolio in the data-collecting companies.

Harmonizing the Material Nomenclature (Standard Materials)

So-called standard materials were defined in order to handle the large variety of materials used within furniture production. The catalogue of standard materials contains 50 categories to classify wooden materials, metal, plastics, and other nonwooden materials as well as packaging materials and operating resources. Table S1 in the supporting information on the Web lists the catalogue of standard materials. All materials identified in the data collection have been assigned to one of these standard materials, which serve as a basis for LCA modeling.

Grouping of the Processes Carried Out (Process Groups)

Not every piece of furniture produced in the factory passes through all production steps. Therefore, so-called process groups were formed to assign the consumption of electric and thermal energy to the product groups manufactured in a furniture factory. A process group represents similar manufacturing processes. Five general process groups were defined, which are shown in table 4. Additionally, table 4 shows the respective criterion for the distribution of the energy demand within a process group to the furniture running through this process group.

Data Collection

The yearly consumption of different materials and energy as well as the amount of products and waste were assessed at company level. It is necessary to collect all material data at a mass basis to ensure that all processes are fully accounted for. To guarantee this, a data validation by mass balance was

Table 4 Process groups and their criteria to distribute the energy demand

Process group index	*General description*	*Criterion for distribution of the energy used within this process group*
G	Coating/veneering	Coated surface area in m²
H	Machine shop/machining	Number of processed workpieces
I	Surface finishing/varnishing	Varnished surface area in m²
J	Assembling and packaging	Mass of furniture in kg
K	(finished products) Warehouse	Mass of furniture in kg

Note: m^2 = square meters; kg = kilograms.

carried out after completing the input-output table at company level. Further, exemplary BOMs were collected to assign the validated data to the product groups as well as the functional groups by calculating the distribution formulas for the materials and energy used.

Data Calculation and Life Cycle Inventory

Defining Virtual Average Furniture

The LCIs obtained by applying the presented method refer to virtual average furniture classified to product groups and functional groups. These average LCIs guarantee that data as collected at company level are contained proportionally in the average products. The calculation procedure is a combination of *top-down approach* and *bottom-up approach*. There are three levels to be considered: (1) the material and energy fluxes at company level; (2) specific pieces of furniture (exemplary BOM); and (3) virtual average furniture. For a graphic illustration and further description of the basic concept, please see section 3 of the supporting information on the Web.

Assigning of Company Material Input Data to Product Groups

The approach to calculate distribution formulas as well as to assign company level data to virtual average furniture is presented in detail in figure 1.

The calculation of the distribution formulas (left side of figure 1, bottom-up) was realized by extrapolation of the material content per BOM to product group level and subsequently to company level. The product group shares of the total materials contained in the product portfolio form the distribution formulas for the following data calculation. Thus, these distribution formulas were applied to the company-level data in the next step. Following this, the LCIs within the product groups were divided by the number of pieces respectively by the mass of furniture, which is represented by the product group. This calculation step creates the LCI for the declared unit (right side of figure 1, top-down). The result of the developed method is the company-level data assigned to the virtual average furniture, including the processes necessary to produce these average pieces of furniture.

Assigning of Company Energy Input Data to Product Groups

The energy demand of the company (electric and thermal) was assigned to the product groups in a two-step approach. First, the total energy consumption had to be distributed among the defined process groups. Because the process groups normally represent specific units of organization within the company, for example, certain workshops, this distribution could be easily done. Second, the further calculation from the process groups to the product group was achieved using the criteria as shown in table 4.

Systematic Data Processing Tools

Within the presented method, it is essential to define a calculation routine. The overall aim is that all company-specific data sets are treated the same way and thus the data processing for each data set is reproducible and identical. Excel tools were established for preparation of the LCIs. At first, a tool was developed to calculate the distribution formulas. Subsequently, a second tool was developed to validate the data collected at company level and to calculate the LCIs by using the distribution formulas generated.

Practical Implementation (Case Study)

A systematic LCA for industrially produced furniture was carried out using the developed method based on the work of Wenker and Rüter (2015) and Wenker (2015). A comparison between the different declared units described in this study is not intended. The main intention of the presented data is to support the furniture companies in optimizing the environmental performance of furniture and in monitoring their process performance with regard to material and energy consumption.

Scope Definition and Methods

System Boundary

The system boundary within this study corresponds to the EN 15804 definition from *cradle-to-gate-with-options*. Figure 2 illustrates the chosen system boundary.

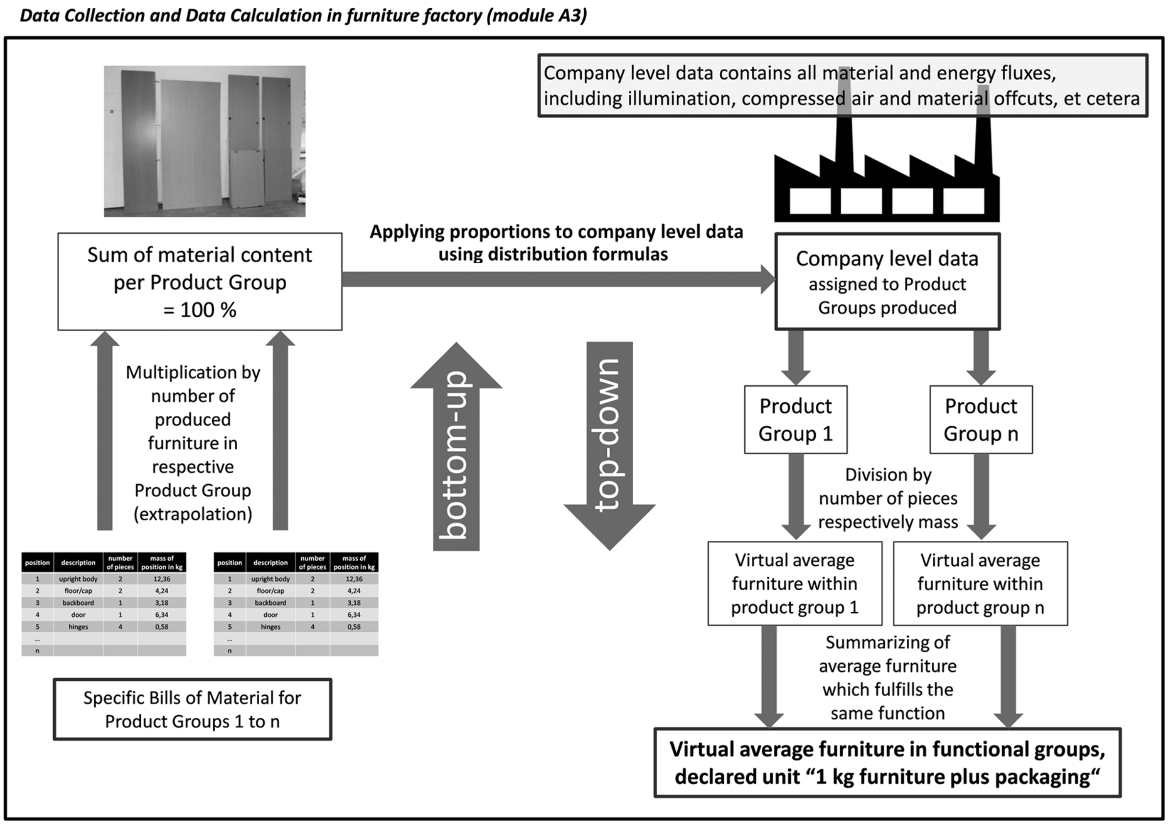

Figure 1 Schematic illustration of the procedure for assigning the company-level data to the virtual average furniture in the product groups. kg = kilogram.

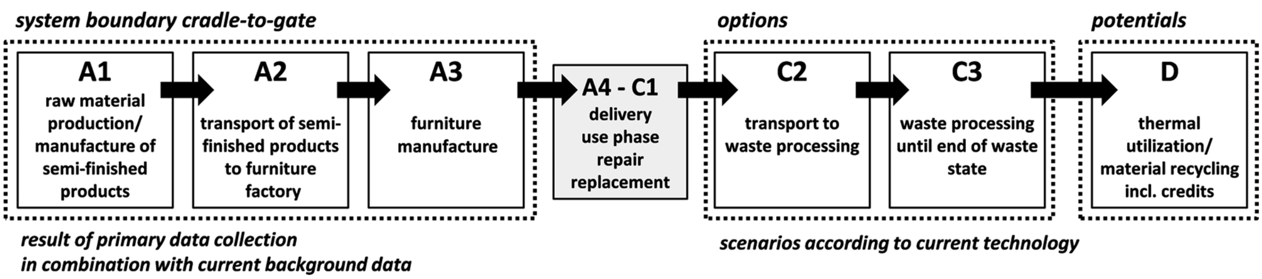

Figure 2 System boundary/modules according to EN 15804. incl. = including.

This study includes the production stage, including raw material production/manufacturing of semifinished products (module A1), transport (A2), and furniture manufacturing (A3). Additionally, the end-of-life (EOL) modules, transport (C2) and waste processing (C3), are considered as scenarios. The benefits and loads resulting from recycling of the furniture after reaching the end of waste state are provided as additional information beyond the system boundary of the product´s life cycle (D).

Accounting of Material-Inherent Properties

Following EN 15804 (CEN 2013) and EN 16485 (CEN 2014), wood-inherent carbon (i.e., carbon contained in the wooden biomass) and primary energy used as raw material have to be accounted for as material-inherent properties. Thus, the transfer of wood-inherent carbon to the product system is considered as input to modules A1 and A3. The carbon content, expressed as carbon dioxide (CO_2), is counted as negative value (–1) within the *global warming potential* (GWP) parameter if wood originates from countries accounting for Article 3.4 of the Kyoto Protocol or from forests that are operating under established forest certification schemes regarding sustainable forest management (CEN 2014). Carbon outputs are reported as CO_2 emissions (+1) in modules A1 and A3 if the wood is burned for energy generation within the manufacturing process, in module A5, which represents the installation process at the customer, in the case of material use of wood for packaging, and in EOL module C3 for the material use of wood in the actual product. Hence, regarding the system boundary according to EN 15804 and EN 16485, the biogenic carbon balance of a wood product is deemed to be neutral throughout its entire life cycle considering all modules from A to C.

A similar accounting was done for *use of renewable primary energy resources used as raw materials* (PERM) and *use of nonrenewable primary energy resources used as raw materials* (PENRM). According to EN 15804 and EN 16485, primary energy used as material enters the product system (+1) in the modules, A1 (product) and A3 (packaging), and is again exported from the product system (–1) in modules A5 (packaging) and C3 (product). Because the module A5 is not considered in the present study, the amount of primary energy contained in the product packaging (PERM/PENRM) is, in this study, exported from module C3 instead of A5 to complete the balance of material-used primary energy.

End-of-Life Scenario

The primary data collection took place at the furniture production sites (module A3) and thus was complemented with an EOL scenario. Postconsumer furniture is chipped to waste wood chips (module C3). These waste wood chips, together with plastic materials, are used for energy generation in module D. All waste-to-energy incinerations produce energy, so credits were given for steam and electricity within module D, which is outside the system boundary of the product system under study. Steam and electricity produced substitute steam from natural gas, respectively, electricity from the German electricity mix. Material recycling was modeled for fittings and other steel components. The recycled steel substitutes steel sheets from an average German steel production site, and these credits were given in module D outside the system boundary.

Functional Groups and Declared Unit

Within this study, average data are provided for the functional groups *storage furniture (enclosed space)* as well as *storage furniture (surface area)*. The declared unit *1 kg furniture plus packaging* is calculated for each functional group.

Primary Data Collection

Primary data collection took place at three furniture production sites from 2011 to 2014. The long period of data collection is attributed to the subsequent method development. Each factory-specific data set refers to the production quantities over a 12-month period. Hence, the total production volume under study amounts to approximately 2.8 million pieces of furniture for a 1-year period with an approximate weight of 190 million kg.

Software, Generic Data, and Method for Environmental Impact Assessment

The LCA case study was conducted using the GaBi 6 software, including its underlying database (PE International 2014). A parameterized basic model was created, which acts as a blueprint for factory-specific and functional group-specific modeling. Generic data serving as background data were drawn from Rüter and Diederichs (2012) for wood-based products and from the GaBi professional database (version 6.108) (PE International 2014). For the environmental impact assessment, CML methodology (Guinée et al. 2002) was used as required in the current version of EN 15804.

Results of the Case Study

Note that, within this publication, production-volume-weighted numbers are displayed. Therefore, only results for two of four functional groups are presented.

Results of the Life Cycle Inventory

Table 5 provides the inventory analysis for the production of 1 kg *storage furniture (enclosed space)*, respectively, 1 kg *storage furniture (surface area)*, at furniture production-site level. Data obtained from the factory sites are related directly to the furniture production. The energy demand and the operating resources used for the production of the co-product *wooden trim waste for sale* (double-output process) could not be assessed. The contribution to the overall monetary revenue generated by this co-product is less than 1 % within all companies under study. Thus, in line with EN 15804, no allocation was done and the energy demand and operating resources related to the co-product were included in the LCA of the furniture following a conservative approach.

For the transport of the semifinished products to the furniture production site, a mass-weighted average distance was calculated from the manufacturer's data. This distance is 188 kilometers (km) for *storage furniture (enclosed space)* and 345 km for *storage furniture (surface area)*.

Results of the Life Cycle Impact Assessment

The detailed results of the environmental impact assessment and the primary energy demand are shown in table 6.

In this case study, the life cycle impact assessment focuses on the widely used environmental parameters (GWP and so on) (see table 6) and the use of primary energy. The contribution of wood-inherent carbon fluxes to the parameter GWP is considered according to the method described above. As a result, GWP within module A1 is –0.712 kg CO_2-eq (equivalents) for *storage furniture (enclosed space)* and 0.744 kg CO_2-eq for *storage furniture (surface area)*. The wood-inherent carbon balance equals zero within the whole product system (modules A1 to C3). As a consequence, the sum of the modules A1 to C3 shows the fossil CO_2-eq amount for producing 1 kg of furniture. Fossil emissions count for 0.867 kg CO_2-eq (*storage furniture [enclosed space]*), respectively, 1.810 kg CO_2-eq (*storage furniture [surface area]*). The sum within the considered parameters, PERM and PENRM, equals zero when pointing at the whole system (modules A1 to C3) (see table 6). Because energy recovery of postconsumer furniture was assumed (apart from the metal components), we find the primary energy used as material (PERM and PENRM) exported from module C3 and subsequently entering module D as an input within the parameters of primary energy used as energy (PERE and PENRE).

Table 5 Inventory analysis for the production of furniture (module A3, furniture production site) comprising (a) inputs and (b) outputs

(a) Inputs			
	1 kg storage furniture (enclosed space) plus packaging	*1 kg storage furniture (surface area) plus packaging*	*Unit*
Wood and engineered wood products			
Remaining in finished product: particleboard (raw, melamine coated, veneered)	0.840	0.611	kg
Remaining in finished product: fiberboard (raw, melamine coated, veneered)	0.046	0.005	kg
Remaining in finished product: lumber (softwood and hardwood)	2.37E-04	0.00E+00	kg
Co-product: diverse levels of prefabrication regarding particleboard, fiberboard, and lumber ending up as coproduct	0.105	0.159	kg
Remaining in finished product: purchased furniture parts (corpus and front parts)	0.022	0.00E+00	kg
Coatings			
High-pressure laminate, melamine-coated decor paper, varnish, others	0.019	0.004	kg
Adhesives			
Adhesives based on polyurethane, urea-formaldehyde, polyvinyl acetate, ethylene vinyl acetate	0.002	0.001	kg
Fittings			
Fittings consisting mainly of metal	0.027	0.009	kg
Metal frames and metal drawers	0.004	0.348	kg
Plastics (ABS, PP, PS, PVC, PE, PA, PU)			
Plastic fitting parts, edgebanding material, others	0.007	0.031	kg
Others			
Glass, mirrors, other	0.040	3.93E-04	kg
Packaging			
Paperboard, plastics, other	0.014	0.003	kg
Operating resources			
Oil, grease, cleaning supplies, abrasive belts	3.56E-04	3.68E-04	kg
Diesel for pallet transporters	1.62E-04	3.10E-05	kg
Fresh water	0.240	0.146	kg
Energy demand			
Electricity for production	0.308	0.153	MJ
Electricity for dust extraction	0.176	0.078	MJ
Electricity for compressed air supply	0.073	0.028	MJ
Electricity for illumination	0.047	0.042	MJ
Electricity for other purposes	0.032	0.005	MJ
Heat from oil	0.084	0.020	MJ

(Continued)

Table 5 Continued

(a) Inputs			
	1 kg storage furniture (enclosed space) plus packaging	*1 kg storage furniture (surface area) plus packaging*	*Unit*
Wooden trim waste from production burned for energy generation; Shavings and residues from particleboard, fiberboard and lumber	0.022	0.022	kg
(b) Outputs			
Product			
Furniture	1.000	1.000	kg
Packaging	0.014	0.003	kg
Co-product			
Wooden trim waste for sale	0.105	0.159	kg
Emissions from			
Thermal utilization of waste wood	Determined by background data from Rüter and Diederichs (2012)		
Burning diesel and oil	Determined by background data from Rüter and Diederichs (2012) and GaBi Professional		
Other			
Ashes from thermal utilization of waste wood	Determined by background data from Rüter and Diederichs (2012)		
Residual water	0.240	0.146	kg
Waste			
Paperboard, plastic foil, metal, mixed industrial waste	0.007	0.010	kg

Note: ABS = acrylonitrile butadiene styrene; PP = polypropylene; PS = polystyrene; PVC = polyvinyl chloride; PE = polyethylene; PA = polyamide; PU = polyurethane; kg= kilograms; MJ = megajoules.

Dominance Analysis of the Modules Assessed

CO_2 related to the wood-inherent carbon balance is not considered for purposes of the dominance analysis, because it is assumed to be neutral over the entire life cycle. It is excluded not to cause misleading messages through the assessment of single life cycle phases in the dominance analysis. Further, module D, that is not a part of the product system, is not displayed within the dominance analysis.

For *storage furniture (enclosed space)*, module A1 contributes 79.0% to the parameter GWP in contrast to *storage furniture (surface area)*, where module A1 accounts for 93.7% of the GWP. For *storage furniture (enclosed space)*, module A3 contributes 16.3% to GWP whereas it accounts only for 4.2% of GWP for *storage furniture (surface area)*. The low contribution of module A3 to the LCA results for *storage furniture (surface area)* can be explained by the fact that, for desks with metal frame, only the tabletop is made in the furniture production site whereas the metal components are purchased. For both declared units, it should be mentioned that the parameter *abiotic depletion potential for nonfossil resources* (ADPE) is completely dominated by impacts caused in module A1. These can be traced back to the supply of metal components.

The relative contribution of the modules considered to the environmental parameters is illustrated in figure S3 (supporting information on the Web). Additionally, a detailed dominance analysis of the GWP results (figure S4, table S2) as well as a detailed illustration of the wood-inherent carbon balance (figure S5) can be found in the supporting information on the Web. The detailed dominance analysis of the parameter GWP shows that wood-based panels and metal components, as well as the electric energy demand in the furniture manufacturing process, account for a notable share of the environmental impacts.

Discussion

The result of the method development is an approach for carrying out systematic LCA for complex wooden products. It includes certain complexity reductions through the assignment of data collected at company level to defined product groups in

Table 6 Environmental impact assessment and primary energy demand. Selected modules and parameters according to EN 15804

Parameter	*Unit*	*Manufacturing of semifinished products (A1)*	*Transport to furniture manufactory (A2)*	*Furniture manufacturing (A3)*	*Total cradle to gate (Σ A1-A3)*	*Transport to waste processing (C2)*	*Waste processing until end of waste state (C3)*	*Total cradle to gate with options (Σ A1-C3)*	*Max. deviation +%/–% (A1-C3)*	*Reuse-recovery-recycling-potential (D)*
Results of the LCA: Environmental Impacts and Primary Energy Demand of 1 kg *storage furniture (enclosed space)* plus packaging										
GWP	kg CO_2-eq	−7.12E-01	8.67E-03	1.41E-01	−5.62E-01	9.46E-04	1.43E+00	8.67E-01	+152/-13	−5.17E-01
ODP	kg CFC-11-eq	4.24E-08	1.65E-14	1.17E-09	4.36E-08	1.80E-15	3.12E-12	4.36E-08	+79/-5	−2.69E-11
AP	kg SO_2-eq	2.26E-03	3.87E-05	3.24E-04	2.62E-03	4.22E-06	5.11E-05	2.68E-03	+186/-14	−3.02E-04
EP	kg PO_4^{3-}-eq	3.80E-04	1.05E-05	5.32E-05	4.44E-04	1.14E-06	6.66E-06	4.52E-04	+142/-9	2.96E-05
POCP	kg Ethene-eq	4.33E-04	−1.43E-05	1.28E-04	5.47E-04	−1.56E-06	3.83E-06	5.50E-04	+36/-7	−6.18E-05
ADPE	kg Sb-eq	4.20E-05	4.59E-10	4.50E-08	4.20E-05	5.01E-11	7.60E-09	4.20E-05	+281/-30	−6.14E-08
ADPF	MJ	1.02E+01	1.18E-01	1.80E+00	1.22E+01	1.29E-02	3.15E-01	1.25E+01	+139/-11	−7.96E+00
PERE	MJ	3.35E+00	9.08E-03	1.07E+00	4.42E+00	9.90E-04	1.17E-01	4.54E+00		1.38E+01
PERM	MJ	1.46E+01	0.00E+00	1.52E-01	1.48E+01	0.00E+00	−1.48E+01	0.00E+00		0.00E+00
PERT	MJ	1.80E+01	9.08E-03	1.22E+00	1.92E+01	9.90E-04	−1.47E+01	4.54E+00		1.38E+01
PENRE	MJ	1.17E+01	1.19E-01	2.07E+00	1.39E+01	1.29E-02	4.25E-01	1.43E+01		−7.79E+00
PENRM	MJ	9.20E-01	0.00E+00	1.87E-01	1.11E+00	0.00E+00	−1.11E+00	0.00E+00		0.00E+00
PENRT	MJ	1.26E+01	1.19E-01	2.26E+00	1.50E+01	1.29E-02	−6.82E-01	1.43E+01		−7.79E+00

(*Continued*)

Table 6 Continued

Parameter	*Unit*	*Manufacturing of semifinished products (A1)*	*Transport to furniture manufactory (A2)*	*Furniture manufacturing (A3)*	*Total cradle to gate (Σ A1-A3)*	*Transport to waste processing (C2)*	*Waste processing until end of waste state (C3)*	*Total cradle to gate with options (Σ A1-C3)*	*Max. deviation +%/–% (A1-C3)*	*Reuse-recovery-recycling-potential (D)*
Results of the LCA: Environmental Impacts and Primary Energy Demand of 1 kg *storage furniture (surface area)* plus packaging										
GWP	kg CO_2-eq	7.44E-01	1.61E-02	7.62E-02	8.36E-01	9.35E-04	9.70E-01	1.81E+00	N/A[a]	−8.93E-01
ODP	kg CFC-11-eq	3.75E-08	3.05E-14	1.45E-09	3.90E-08	1.78E-15	2.11E-12	3.90E-08	N/A	−1.21E-11
AP	kg SO_2-eq	5.79E-03	7.16E-05	1.69E-04	6.03E-03	4.17E-06	3.46E-05	6.07E-03	N/A	−2.27E-03
EP	kg PO_4^{3-}-eq	6.18E-04	1.94E-05	3.18E-05	6.70E-04	1.13E-06	4.52E-06	6.75E-04	N/A	−1.53E-04
POCP	kg Ethene-eq	8.01E-04	−2.65E-05	3.87E-05	8.13E-04	-1.55E-06	2.60E-06	8.14E-04	N/A	−3.48E-04
ADPE	kg Sb-eq	2.33E-05	8.50E-10	1.89E-08	2.34E-05	4.95E-11	5.15E-09	2.34E-05	N/A	−4.71E-08
ADPF	MJ	2.18E+01	2.19E-01	7.89E-01	2.28E+01	1.27E-02	2.13E-01	2.30E+01	N/A	−1.03E+01
PERE	MJ	4.09E+00	1.68E-02	6.60E-01	4.77E+00	9.80E-04	7.95E-02	4.85E+00		9.46E+00
PERM	MJ	9.95E+00	0.00E+00	3.54E-02	9.99E+00	0.00E+00	−9.99E+00	0.00E+00		0.00E+00
PERT	MJ	1.40E+01	1.68E-02	6.96E-01	1.48E+01	9.80E-04	−9.91E+00	4.85E+00		9.46E+00
PENRE	MJ	2.41E+01	2.19E-01	9.91E-01	2.53E+01	1.28E-02	2.88E-01	2.56E+01		−9.35E+00
PENRM	MJ	1.25E+00	0.00E+00	4.20E-02	1.29E+00	0.00E+00	−1.29E+00	0.00E+00		0.00E+00
PENRT	MJ	2.54E+01	2.19E-01	1.03E+00	2.66E+01	1.28E-02	−1.00E+00	2.56E+01		−9.35E+00

[a]Deviations are not displayed within the functional group storage furniture (surface area) for reasons of confidentiality because the average values are based on data from two companies.

Note: LCA = life cycle assessment; kg = kilogram; GWP = global warming potential; ODP = (stratospheric) ozone depletion potential; AP = acidification potential of land and water; EP = eutrophication potential; POCP = photochemical ozone creation potential; 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; PERT = total use of renewable primary energy resources; 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; PENRT = total use of nonrenewable primary energy resources; eq = equivalents; CO_2 = carbon dioxide; CFC-11 = trichlorofluoromethane; SO_2 = sulfur dioxide; PO_4^{3-} = phosphate; Sb = antimony; MJ = megajoules; Max. = maximum; N/A = not applicable.

order to build the LCA model. This is to ensure that no material or energy consumption caused by the whole factory is neglected. Therefore, the developed approach is a promising procedure to systematically generate LCA results for industrially produced furniture and other complex wooden products. The advantage resulting from the combination of the *top-down approach* and *bottom-up approach* can be summarized with the words from Weidema (2004, 61): “By integrating the two data sources in one database approach, it is possible to ensure completeness while still providing the necessary detail in process modelling.” On the one hand, this means that the total inputs used for the furniture production are considered in any case by the top-down data collection (completeness) for the research carried out in the present article. On the other hand, the analysis can be carried out at the desired level of detail by the formation of an a priori unlimited number of product groups (necessary detail). The LCA results thus provide average values, which are representative for processes and products in the whole furniture production site.

A sensitivity analysis shows that neglecting infrastructural energy demands, operating resources, and production waste in the furniture industry ends up in missing up to roughly 10% of the overall impacts. When performing a BOM-based LCA, the overall impact for the parameter GWP is covered by 90.7% for *storage furniture (enclosed space)* respectively 97.2% for *storage furniture (surface area)*. The infrastructural electricity demand (electricity for dust extraction, supply of compressed air, and illumination) mainly contributes to the missing 10%. The magnitude of the missing impacts depends on the level of the vertical integration in the particular company. Details on this issue can be found in section 6 of the supporting information on the Web.

The maximum of assessed product groups per company was 12, although the approach does not limit the product groups under investigation. In future studies, the level of detail should be increased by assessing more product groups with every product group representing fewer pieces of furniture. This is to decrease the variability within a single product group. Therefore, it is necessary to enhance the performance of computing and data processing in the furniture industry, especially for purposes of LCA. Enterprise resource planning systems can be powerful tools to support data collection in the context of LCA. Data processing in the furniture industry should be toughened up to support a more detailed LCA, even in companies with lot size one production.

Assigning Company-Level Data to Defined Product Groups

Material amounts collected at the company level were assigned to virtual average furniture. To cross-check the assignment of company-level data to virtual average furniture, a comparison between the calculated average piece of furniture in each product group with the underlying representative BOM was arranged. Thereby, the product mass of the BOM is exclusively used for cross-checking purposes and not used to assess environmental impacts. In two companies, a good match could be found between the product mass of the exemplary BOM and the calculated product mass of the virtual average piece of furniture. The difference is less than 10% for all considered product groups in these two companies. In another company, discrepancies of –46% to –52% were discovered. That means that the masses of the exemplary BOM were higher by approximately a factor of 1.5 than the mass of the determined virtual average furniture. The discrepancies are large, but the variability in the discrepancies is very low. Because all BOM have an above-average mass in the same range, this has no effect on the relative distribution formulas. Only the case where one single product group shows a highly different discrepancy to other product groups is there an indicator for an inappropriate selected exemplary BOM. However, single product groups pointing to an increased discrepancy between BOM and virtual average furniture can be easily detected.

The distribution criteria from table 4 have to be discussed. The distribution of energy consumption in the process groups *coating* as well as *surface finishing* on the basis of the square meters (m^2) processed is deemed to be very accurate. Likewise, the mass of furniture for the distribution of energy consumption within the process groups *assembling* and *warehouse* appears to be a plausible indicator. In contrast, the number of processed workpieces for energy distribution within the process group *machining* is not an exact criterion, although it is certainly an important indicator. Future development will create options to capture the energy demand more precisely by combining LCA information with energy management systems according to ISO 50001 (ISO 2011).

Verification of the Developed Method’s Performance and Reliability by Applying to Primary Data

From the results of the case study, it can be concluded that the approach allows LCA data for various product groups or functional groups to be gained with simultaneous consideration of all material and energy fluxes at company level. Thus, the method´s performance and reliability could be verified. As a prerequisite of the developed method, it must be mentioned that a suitable data structure in the company is required to report the material fluxes at company level and the energy fluxes at process group level.

Geographic Representativeness and Quality of the Data

Within the reference period of 1 year, the total production of the three companies under study amounted to 2.8 million pieces of furniture. Because, in 2013, approximately 103.3 million pieces of furniture were produced in Germany (German Federal Statistical Office 2014; VDM 2014), the products under investigation in the present study correspond to 2.7% of Germany’s annual furniture production.

All company-specific data were communicated directly by the companies. The data were checked for plausibility by the companies as well as by the LCA practitioner. Therefore, it can be assumed that the data are of overall good quality. The quality of the background data from Rüter and Diederichs (2012) is well documented. Data sets used from the GaBi Professional database cannot generally be assessed in terms of their quality. The data-set–specific documentation (PE International/thinkstep 2015) only provides information in particular cases. It can be stated, however, that none of the background data sets used is older than 10 years.

Findings and Implications

Although no general comparison between the declared units is drawn, some general findings and conclusions can be derived from the LCA results.

The production of nonwooden components in module A1 accounts for a considerable share of the LCA results of the entire manufacturing phase of furniture (modules A1 to A3). Especially, the metal components in module A1 play an important role within the GWP of furniture produced. Further, the parameter ADPE is strongly influenced by the production of the metal components. This is in particular the case, when scarce resources, such as zinc, are used.

Wooden materials and their manufacturing in module A1 also account for a notable share in the LCA results within the cradle-to-gate phase of the declared units (modules A1 to A3), although the production of wood-based materials shows a relatively low environmental impact. This is because wooden materials represent the largest mass fraction of the declared units.

Module A3 accounts for a comparatively small share of the LCA results within the considered system boundary cradle-to-gate with options. Pointing at the parameter GWP (without wood-inherent carbon), its contribution ranges from 4.2% for *storage furniture (surface area)* up to 16.3% for *storage furniture (enclosed space)*. The wide range is caused by the different material composition of these types of furniture. *Storage furniture (enclosed space)* contains a high proportion of wood-based materials, which are processed in the furniture production site. In contrast, *storage furniture (surface area)* considered within this study is strongly influenced by office furniture and therefore has a higher metal content. Thus, *storage furniture (surface area)* shows a lower level of vertical integration in the furniture factory.

The variability in environmental impacts between the functional groups (which means, at the same time, variability between product groups and, in consequence, single products) can be traced back to the different material composition and different production processes required. Various products within one product group, of course, show variability in environmental impacts. The more products summarized in one product group, the higher the variability. Especially, the metal content is a strong driver for variability in LCA results (see table 5 and the resulting dominance of metal in table S2 in the supporting information on the Web).

Conclusions

The developed method allows the conduct of a systematic LCA for cradle-to-gate phases of industrially produced furniture as an example for complex wooden products. Through its practical implementation (case study), LCA data for the functional groups *storage furniture (enclosed space)* and *storage furniture (surface area)* were generated.

The developed procedure is a combination of the *top-down approach* (data collection at company level) and the *bottom-up approach* (calculation of the distribution formulas for assigning company-level data to the defined product groups). Using this approach, completeness and representativeness (data collection at company level) as well as required detail (analysis of an a priori not limited number of product groups) can be ensured at the same time. The method could be proved to be feasible for application in the furniture industry. It is expected that the quality of the LCA results obtained will be improved by the developed method, especially in terms of completeness.

From the discussion of LCA results, one can conclude that the presented research results provide viable LCA data for wood-based furniture. The LCA case study covers 2.7% of Germany's annual furniture production, based on the number of produced pieces of furniture. Therefore, the results obtained are useful as a first estimate of the potential environmental impacts of wood-based furniture produced in Germany. Extensive data collection is still needed to increase the representativeness of the LCA data at the geographical level. The dominance analysis carried out reveals that the use of fittings and other metal components notably influence the LCA results. In addition, the use of wood and EWPs considerably affect the LCA results because wooden materials represent most of the overall mass of the products under study. All in all, the supply of semifinished products, which is covered by module A1 according to EN 15804, accounts for the highest impact on the LCA results. Consequently, for furniture-producing companies, the selection of the materials used offers the greatest potential for reducing environmental impacts.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information contains six sections providing additional information on specific aspects from the research article. Section 1 gives a detailed description of the industrial furniture manufacturing process. Section 2 gives an overview of the standard materials for categorizing the diverse materials used within furniture production. Section 3 provides a graphic illustration and a description of the basic concept of the developed method. Section 4 illustrates and further deepens the dominance analysis carried out from the life cycle assessment (LCA) case study´s life cycle impact assessment results. Section 5 gives a detailed illustration and description on the wood-inherent carbon balance, which was assessed according to EN 16485. Finally, section 6 provides a sensitivity analysis where the LCA carried out using the developed approach is compared to an LCA neglecting infrastructural energy demands, operating resources, and production waste as a bill of materials-based (BOM-based) LCA most likely would do.