



Life cycle assessment of a hot-pressing machine to manufacture particleboards: hotspots, environmental indicators, and solutions

Diogo Aparecido Lopes Silva¹ · Alessandro Silveira Firmino¹ · Fabiane Salles Ferro² · André Luis Christoforo³ · Florence Rezende Leite⁴ · Francisco Antonio Rocco Lahr⁵ · Karel Kellens⁶

Received: 26 December 2018 / Accepted: 13 April 2020 / Published online: 26 May 2020
© Springer-Verlag GmbH Germany, part of Springer Nature 2020

Abstract

Purpose Green manufacturing (GM) is the environmental benign manufacturing of products with a minimal negative impact on the natural environment. Research studies on GM have increased in the last years with attention to the application of life cycle assessment (LCA). However, the manufacturing industry still faces some barriers and challenges that hinder a proper practical integration of GM using LCA. Accordingly, this paper performs an LCA-based GM case study of a wood-based industry that produces particleboards to investigate environmental hotspots and suggests GM indicators and solutions for a hot-pressing machine tool.

Methods A case study of a wood-based industry that produces particleboards in Brazil was designed. A LCA-based GM framework was developed and applied according to its three phases: pre-assessment, environmental assessment and monitoring, and post-assessment. Each phase is composed of specific stages and each stage has its own activities and goals. To quantify the environmental life cycle impacts, the ILCD midpoint method with 13 impact categories was selected. Based on these environmental impacts, a set of indicators and solutions was designed to improve the product life cycle impacts through a greener manufacturing process of particleboards. A cradle-to-grave approach was used to model the particleboard life cycle and the manufacturing phase was modeled based on the unit process life cycle inventory (UPLCI) methodology.

Results and discussion The particleboard manufacture was designed into five unit processes and results of the pre-assessment showed that the hot-pressing unit was the most relevant process because of its direct and indirect impacts mainly to human toxicity cancer effects, global warming, and photochemical ozone formation. During the environmental assessment and monitoring phase, the hot-pressing machine was then investigated based on the main contributors to the caused environmental impacts, i.e., electricity consumption and air emissions of free formaldehyde, as well as in terms of its most relevant process parameters: pressure (P) and temperature (T). Opportunities to reduce up to 21% upstream impacts and up to 41% downstream impacts were identified from making simple changes to the hot-pressing parameters. Further investigation in the post-assessment revealed that environmental impacts can be estimated based on the applied P and T values and GM indicators were suggested.

Responsible editor: Zbigniew Stanislaw Klos

✉ Diogo Aparecido Lopes Silva
diogo.apls@ufscar.br

¹ Department of Production Engineering, Research Group on Sustainability Engineering, Center for Science and Technology Management, Federal University of São Carlos, Rodovia João Leme dos Santos, km 110 – SP-264, Sorocaba, SP 13565-905, Brazil

² Department of Forest Engineering, Midwestern State University, PR 153 - km 7, s/n - Riozinho, Irati, PR 84500-000, Brazil

³ Department of Civil Engineering, Federal University of São Carlos, Rodovia Washington Luis, km 235, SP-310, São Carlos, SP 13565-905, Brazil

⁴ São Paulo State University, Três de Março Avenue, 511, Alto da Boa Vista district, Sorocaba, SP 18087-180, Brazil

⁵ Department of Structures Engineering, School of Engineering of São Carlos, University of São Paulo, Av. Trabalhador São-Carlense, São Carlos, SP 13566-590, Brazil

⁶ Department of Mechanical Engineering, KU Leuven, Campus Diepenbeek, Wetenschapspark 27, 3590 Diepenbeek, Belgium

Conclusions The proposed GM framework can be used in other case studies to integrate GM + LCA in practice. Results of the case study application showed that the hot-pressing machine was a hotspot into the cradle-to-grave life cycle impacts of particleboards and the proposed GM indicators can be used to predict life cycle impacts at manufacturing level.

Keywords Green manufacturing of particleboards · Green manufacturing indicators · Assessment criteria and indicators · Life cycle assessment of manufacturing

1 Introduction

Green manufacturing (GM) is a rather new research topic which has made remarkable advances in the last few years. GM is concerned about the environmental impacts of manufacturing processes, which for Garetti and Taisch (2012) is crucial for a sustainable development as a whole.

The concern with sustainability issues in manufacturing became more prominent in the 1990s. In fact, the concept of GM was first introduced more than two decades ago as environmentally conscious manufacturing (Florida 1996). Since then, scientific publications have intensified mainly from 2010 (Silva et al. 2016), with focus on topics such as life cycle assessment (LCA) (Kellens et al. 2012a, b; Kim et al. 2015), real-time and online monitoring of manufacturing environmental aspects (Filleti et al. 2014, 2017; Silva et al. 2018; Vikhorev et al. 2013), and the selection of GM technologies (Jin and Noh 2014; Li et al. 2010a, b) and GM indicators (Joung et al. 2012).

1.1 Typical gaps in GM using LCA

Dornfeld (2014), Li (2015), and Shin et al. (2015) explain that the manufacturing industry still faces some barriers and challenges that hinder a proper practical integration of GM using LCA. Some typical gaps are as follows:

- Literature reviews show that so far, no relevant efforts have been made to enable manufactures to make decisions on their environmental performances through primary data collected from their own shop floor operations. Further, additional efforts are needed to develop comprehensive theoretical propositions (e.g., models, tools) that encompass assessment, diagnosis, and optimization for environmental improvements in manufacturing processes and in a product's life cycle perspective as well (Shin et al. 2015).
- To support an effective implementation of GM at the shop floor area, Kellens et al. (2012a, b) have contributed to the development of a systematic methodology for inventorying manufacturing unit processes to support industrial groups and researchers to use datasets with high quality in LCA applications—the unit process life cycle inventory (UPLCI) methodology. However, the UPLCI only considers the part production phase and its corresponding

manufacturing unit processes and it does not cover the complete product's life cycle perspective.

- Environmental assessment and monitoring should be designed considering experiments and simulations at the shop floor area by collecting real-time data in manufacture phase of products in order to select relevant GM scenarios (Chompu-inwai et al. 2015; Filleti et al. 2017; Silva et al. 2015; Singh et al. 2015). However, many GM studies are still based only on general LCA results.
- Joung et al. (2012) point out that the manufacturing industry needs an open, simple, and neutral set of indicators to measure and monitor sustainability of manufactured products and manufacturing processes. However, most GM indicators still focus on monitoring environmental aspects of manufacturing unit processes (resource consumption, waste, and emissions) instead of environmental impacts of them (climate changes impacts, human health impacts, ecotoxicological impacts, etc.). The use of statistical tools is also desired here in order to predict the overall life cycle impacts of products (Gloria et al. 2014; Igos et al. 2019) according to a manufacturing unit process under interest.

To overcome these managerial gaps, an in-depth evaluation of manufacturing unit processes is needed, as the LCA-based GM approach proposed on this paper and described in Section 2.

1.2 GM initiatives in the wood-based sector

Another relevant issue is that GM studies are still more focused on machining processes (Aurich et al. 2013; Silva et al. 2016), such as grinding (Filleti et al. 2014, 2017; Linke and Overcash 2012; Silva et al. 2018), turning (Araujo and Oliveira 2012; Jeswiet and Kara 2008), milling and drilling (Jiang et al. 2012; Zendoia et al. 2014), and additive manufacturing (Kellens et al. 2017a, b). On the other hand, GM studies for the wood-based sector are less numerous.

In the wood sector, reconstituted wood panels are those that are manufactured with small pieces of wood or other lignocellulosic materials (e.g., chips, flakes, strands, shreds, or fiber) agglomerated with a resin type as binder and controlled by a set of temperature and pressure parameters. Among the different types of wood panels, the particleboard is one of the most consumed and produced in the world. Brazil stands out

among the world's largest producers, since it has advanced technology in the production of particleboards. It is also the country with the largest number of state-of-the-art factories due to the continuous investments in technology and automation as well as the modernization of existing plants (Weber and Iwakiri 2015). The uses of wood panels are mostly applied in the production of furniture, such as tabletops, wardrobes, cupboard sides, shelves, and dividers and secondarily in civil construction applications such as wood floors (Iritani et al. 2015; Silva et al. 2013; Ferro et al. 2018a, b).

There are various LCA studies to determine the environmental profile of products within the wood-based sector (Klein et al. 2015). However, these LCA studies show many differences concerned to the definition of the system boundaries (cradle-to-gate vs cradle-to-grave) as well as to the life cycle inventory and data quality (primary or secondary data). Table 1 summarizes the LCA studies with focus on particleboards. Most of the studies are from 2010's and from the USA and Brazil.

Some GM initiatives can be identified from studies in Table 1, such as substitution of wood by residues to produce particleboards (Santos et al. 2014; Silva et al. 2013), changes on energy supply for the factory (Garcia and Freire 2014; Rivela et al. 2006; Silva et al. 2013; Wilson 2008, 2010), and suggestions to reduce free formaldehyde air releases coming from the hot-pressing manufacturing processes (Nakano et al. 2018; Silva et al. 2013). On the other hand, none of these studies has evaluated the effect of manufacturing unit

processes under the overall life cycle impacts of particleboards including upstream and downstream life cycle impacts. None of these studies have used the UPLCI methodology for the life cycle inventory of manufacturing unit processes and neither suggestions of GM indicators were found until now.

Thus, the current paper aims at filling this gap by providing a detailed LCA-based GM case study of particleboards in Brazil, with focus on an in-depth evaluation of manufacturing unit processes to indicate forms to reduce life cycle hotspots and suggests GM indicators.

The novelty of this paper is the proposal of a GM framework (see Section 2) by including the following topics: integration of LCA with real-time monitoring of manufacturing environmental aspects and generation of GM indicators based on life cycle perspective and impacts of products for decision-making.

2 Methodology

A single case study was designed for a wood-based industry in Brazil, which produces particleboards for the domestic market. The step-by-step activities for the case study execution are described below:

- *Literature review*: as presented in Table 1, publications involving studies on LCA for the particleboards production were searched and reviewed to collect relevant

Table 1 List of recent LCA papers focusing on particleboards production

Authorship	Year	Country	Goal of the study	Approach	Functional unit
Silva et al.	2013	Brazil	LCA of particleboard produced in Brazil	Cradle-to-gate	1 m ³ of particleboard
Silva et al.	2014	Brazil	Comparative LCA of particleboards made with and without aggregation of sugarcane bagasse residues	Cradle-to-gate	1 m ³ of particleboard
Santos et al.	2014	Brazil	Comparative LCA of particleboards made of residues from sugarcane bagasse (<i>Saccharum</i> spp.) and pine (<i>Pinus elliottii</i>)	Cradle-to-grave	1 m ² of particleboard
Rivela et al.	2006	Spain	Life cycle inventory of particleboards	Cradle-to-gate	1 m ³ of particleboard
Kouchaki-Penchah et al.	2016	Islamic Republic of Iran	LCA of flat pressed particleboard production in the Islamic Republic of Iran	Cate-to-gate	1 m ³ of particleboard
Garcia and Freire	2014	Portugal	Carbon footprint of particleboards produced in Portugal	Cradle-to-gate and cradle-to-grave	1 m ³ of particleboard
Wilson	2010	USA	Life cycle inventory of particleboards in terms of resources, emissions, energy, and carbon	Cradle-to-gate and cradle-to-gate	1 m ³ of particleboard
Wilson	2008	USA	Life cycle inventory of particleboards	Cradle-to-gate	1 m ³ of particleboard
Puettmann et al.	2013	USA	LCA of US particleboards production	Cradle-to-gate	1 m ³ of particleboard
Nakano et al.	2018	Japan	LCA of wood-based boards produced in Japan and impacts of formaldehyde emissions during the use stage	Cradle-to-gate and cradle-to-grave	1 m ³ of particleboard

literature data for this study. The literature results were used within Section 3 to support suggestions of green manufacturing alternatives to produce particleboards.

- *Pre-assessment of the company:* a prioritization matrix was used to support the selection of a standard particleboard model to be used as a baseline for the LCA. This step was important because there is a mix of different particleboards as described in more detail in Section 2.2. After that, a field data collection was performed at the company level to analyze its documentation about materials and energy consumptions as well as waste generation and emissions to produce the selected particleboard. The main strategies for the field data collection include a semi-structured questionnaire with open-ended questions sent to the technical team of the particleboard company. Results of the field data collection were used to complete the life cycle inventory of particleboards in Section 2.3.
- *A general LCA of the standard particleboard:* the ISO 14040 and 14044 standards (ISO 2006a, b) were used to evaluate a cradle-to-grave LCA for the standard particleboard as described in Sections 2.2, 2.3, and 2.4.
- *Environmental assessment and monitoring:* from the general LCA results, environmental hotspots were identified, and green manufacturing scenarios are set up in Section 3.1. A manufacturing unit process was selected because of its representativeness on the general LCA results and experiments and simulations were designed for the definition of GM scenarios and indicators. For this, the UPLCI methodology (Kellens et al. 2012a, b) and a multivariate regression model evaluated by analysis of variance (ANOVA) were applied.
- *Post-assessment:* selection of green manufacturing scenarios and indicators in Section 3.2, in order to reduce the life cycle environmental hotspots at manufacturing level. Most of the GM indicators are still focused on both monitoring resource consumption and manufacturing emissions (Joung et al. 2012) instead of the monitoring of environmental impacts. Thus, this paper suggests the use of regression models to predict the overall life cycle impacts of products according to the manufacturing unit process under interest.

2.1 Key points for the case study

The study has been performed in collaboration with a particleboard producer, with a production capacity of 35,000 m³/month, located in the São Paulo State in Brazil. This company is one of the biggest ones in the country representing approximately 40% of the market share and its products are mainly consumed by furniture producers for commercial and residential use. Figure 1 shows an overview of the product and its main applications.

The evaluated product in Fig. 1 refers to the particleboard (or medium-density particleboard—MDP), a type composite material made of a synthetic adhesive binder and a reinforcement phase of wood particles arranged in three layers. The adhesive is composed of urea-formaldehyde resin and additives (paraffin emulsion, catalysts), while the particles come from reforested species of eucalyptus wood in Brazil (Silva et al. 2013).

For the case study, the data collection protocol is listed in Table 2 based on Yin (2015) and detailed information about data of particleboards was collected via the questionnaire available in Appendix I.

From the case study results, the most relevant manufacturing unit process was selected for an in-depth assessment and monitoring of environmental aspects and impacts. According to results that will be presented in Section 3, this process was the hot-pressing machine. The study of this manufacturing unit process was not carried out directly in the respective particleboard producer due to limitations such as lack of human resources in the company to follow the tests and unavailability of free time for tests at that moment. Thus, an equivalent hot-pressing machine tool was selected for the study, as detailed in Section 3.1. The selected machine is comparable to the hot-pressing machine used by the industrial partner in terms of efficiency, management of the manufacturing processes parameters, and quality of the manufactured products.

Also, multivariate regression model evaluated by ANOVA was designed based on Montgomery (2008) and a set of experiments and simulations were carried out for a hot-pressing machine tool. The outcome of these analyses will be detailed in Section 3.2. It is important to note that the combination of ANOVA and LCA for green manufacturing studies is an important strategy to support decision-making processes towards an environmentally benign manufacturer of products (Chompu-inwai et al. 2015; Filleti et al. 2017; Silva et al. 2015; Singh et al. 2015).



Fig. 1 Overview application of particleboards for furniture manufacture

Table 2 Data collection protocol for the case study

Main procedures for data collecting	
Visited location	For reasons of confidentiality, the name of the company and people have been preserved on this research. In a beginning contact phase, a cover letter was prepared and sent to the company to show a summary of potential results with the research agenda. After that, a first meeting was scheduled with the particleboard company and its representatives, and activities of A2 were designed.
Activity schedule	A schedule of activities was set up as follows below. Four technical visits have been performed to finish the case study's data field collection: <ol style="list-style-type: none"> 1. A first technical visit for general presentation of the research project, its agenda and needs in terms of data collection and information 2. A second visit to collect data according to the Appendix I questionnaire 3. A third visit for remaining data collection and presentation of partial results of the study 4. One last visit to present consolidated results of the case study Each technical visit lasted an average of 6 h.
Data source and tools for data collection	Data sources and tools for data collection were diversified. However, the main data source was from semi-structured interviews. The interviews were conducted with professionals from various areas within the visited company, such as engineers, supervisors, industrial managers, environment engineers, quality analysts, and product development engineers. <p>All interviews were carried out with attention for the following topics:</p> <ol style="list-style-type: none"> 1. Selection of a product of interest for the company 2. Mapping of all the manufacturing processes for the chosen product 3. Quantification of direct materials and energy inputs and outputs to/from the manufacturing processes 4. An in-depth study of one manufacturing unit process <p>Other sources of data supporting the interviews were documentation analyses and direct observations of the researchers. Documentation analyses were important to cover topics 3 and 4. Finally, a panorama questionnaire (see Appendix I) was designed to guide the interviews.</p>

2.2 Goal and scope definition

Particleboards are marketed based on their nominal thickness and type of finishing coat. Table 3 shows the prioritization matrix used to select the product configuration of interest and the four criteria of R, T, C, and E (Silva et al. 2018) are as follows:

- *Representativeness* (R): Relative importance of a product in the total revenue of the company. 1, low contribution; 3, intermediate contribution; 5, high contribution
- *Trend* (T): What is the market trend for the product sales volume? 1, decay or withdrawal from the market; 3, keep at the same level; 5, increasing sales
- *Cost* (C): Cost of production (from acquisition of raw materials to product shipment): 1, low cost; 3, intermediate cost; 5, high cost
- *Environment* (E): Expected environmental impact that a product can generate from its whole life cycle: 1, low impact; 3, intermediate impact; 5, high impact

From Table 3, the priorities were the panel with 15 mm nominal thickness, with and without coating. However, the studied company selected the uncoated panel because of its representativeness R in the sales volume. Therefore, the selected product was the 15 mm particleboard without coating.

Particleboards are intermediate products and to cover its cradle-to-grave life cycle, a wardrobe model studied by Iritani et al. (2015) was chosen. The wardrobe with 2670 mm × 606 mm × 2323 mm dimensions is made of particleboards and weighs 257 kg.

The LCA goal was defined as the identification of environmental improvements for the particleboard's life cycle. Once the product was defined, the functional unit and reference flow are established in Table 4 and the next step was to define a product system in Fig. 2. The LCA study was divided into four steps as defined by ISO (2006a, b): goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation.

The product system in Fig. 2 shows four life cycle stages. Raw material supply, provide inputs required for the manufacturing stages, use of particleboards to

Table 3 Matrix for prioritization of products

	List of products	R	T	C	E	$R \times T \times C \times E$	Ranking
1.	Particleboard without coating, 15 mm nominal thickness	5	5	3	3	225	1°
2.	Particleboard without coating, 7–12 mm nominal thickness	3	3	3	3	81	3°
3.	Particleboard without coating, 18–25 mm nominal thickness	3	5	3	3	135	2°
4.	Particleboard without coating, >25 mm nominal thickness	3	3	3	3	81	3°
5.	Particleboard with melamine coating, 15 mm nominal thickness	3	5	5	3	225	1°
6.	Particleboard with melamine coating, 7–12 mm nominal thickness	3	3	5	3	135	2°
7.	Particleboard with melamine coating, 18–25 mm nominal thickness	3	3	5	3	135	2°
8.	Particleboard with melamine coating, >25 mm nominal thickness	3	3	5	3	135	2°
9.	Particleboard with finish foil coating, 15 mm nominal thickness	3	3	3	3	81	3°
10.	Particleboard with finish foil coating, 7–12 mm nominal thickness	1	1	3	3	9	5°
11.	Particleboard with finish foil coating, 18–25 mm nominal thickness	1	3	3	3	27	4°
12.	Particleboard with finish foil coating, >25 mm nominal thickness	1	3	3	3	27	4°

R representativeness, *T* tendency, *C* cost, *E* environment

assemble the wardrobe model, and use and post-use phases of the furniture, as well as for some activities of transportation.

A process flow diagram is given in Fig. 3 to represent the manufacturing unit processes in details. Quantification of input and output flows for each unit process will be further discussed in Section 2.3.

In Fig. 3, some intermediate flows are highlighted; for example, wood particles generation produces 205.6 kg of particles, while hot-pressing produces 234.9 kg of particleboards. These intermediate flows are examples of individual reference flows of each manufacturing unit process, which refer to the LCA functional unit from Table 4. Further information about technologies applied in the production of particleboards can be obtained from Rivela et al. (2006), Silva et al. (2013, 2014), and Wilson (2010).

2.3 Life cycle inventory analysis

For the LCI step, data was obtained from primary and secondary sources. Primary data was collected according to the case study protocol description in Table 2. Direct inventory flows are given in Table 5, where the main inputs to produce particleboards were the consumption of electricity, wood, water, and urea-formaldehyde resin. Secondary LCI data were

extracted from available LCA databases and literature, as described in Table 6.

Table 6 shows that most of the indirect flows were obtained by using the GaBi 6.5 LCI database and software tool. Background data were gathered considering a based-mass cut-off criterion of 95% of all direct flows of the product system. In addition, most of these secondary data were collected for Brazilian conditions, while a smaller portion were from foreign countries due to the unavailability of national respective data for steel, polyethylene, cardboard, and paints and varnishes. Indirect flows due to the capital goods were not included due to the complexity of including this information for each of the five manufacturing unit processes from Fig. 3. On the other hand, in Section 3.2, this information was raised with focus on the manufacturing unit process selected for the GM scenarios and indicators study.

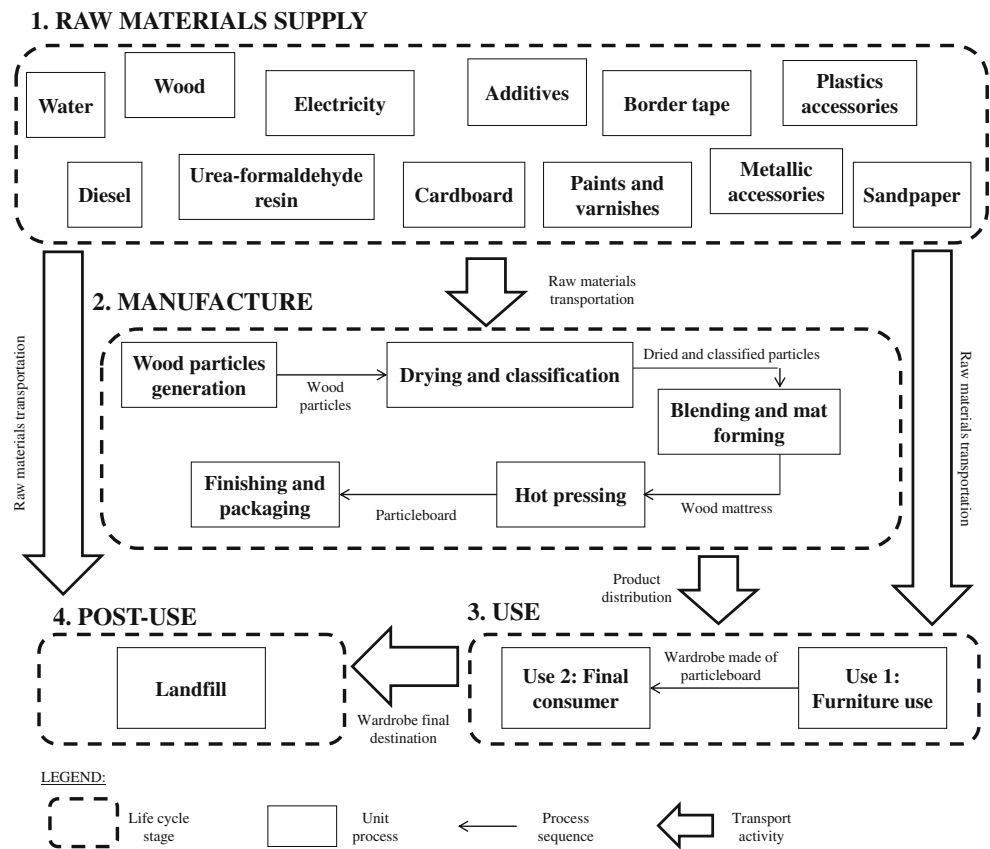
The main assumptions for the inventory of the manufacturing phase were as follows:

- Silva et al. (2013) showed data of electricity consumption of 507 MJ/m³ associated with the particleboard produced in Brazil. Yet, only 70% of this consumption is directly linked to the product manufacturing processes, therefore, 355 MJ/m³. Thus, according to the reference flow of 235 kg of particleboard (panel density 630 kg/m³), a total consumption of 132.4 MJ of electricity was inventoried. This electricity

Table 4 Particleboard: function, functional unit, and reference flow

Product	Function	Functional unit	Reference flow (RF)
Particleboard without coating, 15 mm nominal thickness	Raw material to compose structural parts of wood-based furniture	The use of a wardrobe model made of particleboard, with storage capacity of 40 kg (or 3.7 m ³) of goods for 5 years	The production of 235 kg of particleboard

Fig. 2 Particleboard cradle-to-grave product system



consumption was stratified among the five manufacturing unit processes of Fig. 3, based on the nominal power of the machine tools and operation time of each unit process.

- The consumption of 256.4 kg of wood logs occurs during the *wood particle generation*. However, to calculate the

environmental impacts in Section 2.4, the total amount of wood was proportionally divided among all the manufacturing unit processes according to their generated amount of wood waste. For example, in Table 5, *wood particle generation* produces 14.4 kg of bark and more 36.3 kg of

Fig. 3 Process flow diagram of particleboard manufacture

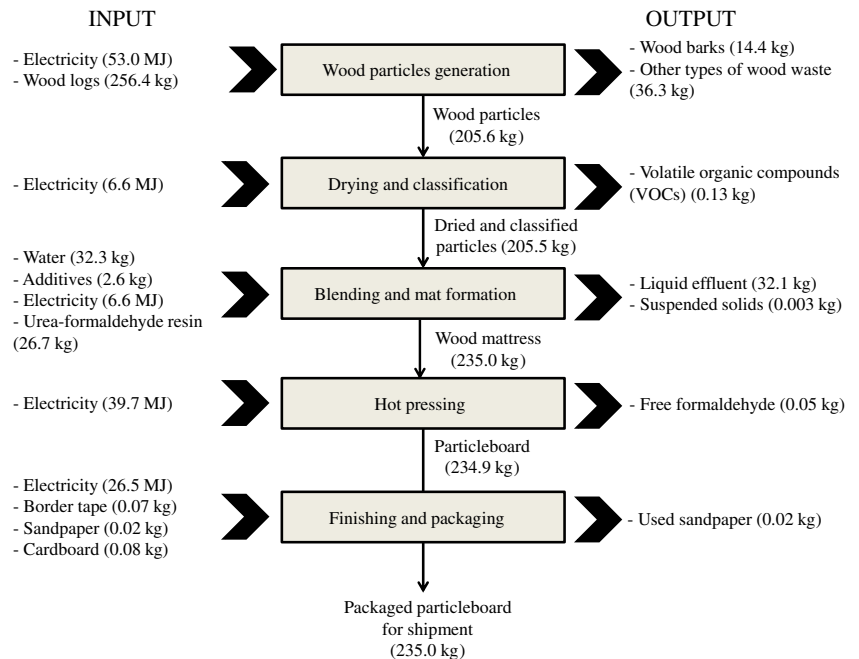


Table 5 Direct inventory flows of the particleboard life cycle

	Inputs		Outputs		
Manufacture	▪ Diesel (transportation of raw materials) ^a	0.6 kg	▪ Carbon dioxide (CO ₂) ^a	1.9 kg	
			▪ Carbon monoxide (CO) ^a	0.002 kg	
	Wood particles generation				
	▪ Electricity	53 MJ	▪ Wood barks	14.4 kg	
	▪ Wood logs	256.4 kg	▪ Other types of wood waste	36.3 kg	
	Drying and classification				
	▪ Electricity	6.6 MJ	▪ Volatile organic compounds	0.1 kg	
	Blending and mat formation				
	▪ Water	32.3 kg	▪ Liquid effluent	32.1 kg	
	▪ Additives (catalyst, paraffin)	2.6 kg	▪ Suspended solids	0.003 kg	
	▪ Electricity	6.6 MJ			
	▪ Urea-formaldehyde resin	26.7 kg			
	Hot pressing				
	▪ Electricity	39.7 MJ	▪ Free formaldehyde	0.05 kg	
	Finishing and packaging				
	▪ Electricity	26.5 MJ	▪ Used sandpaper	0.02 kg	
▪ Border tape	0.07 kg	▪ Particleboard	235 kg		
▪ Sandpaper	0.02 kg				
▪ Cardboard	0.08 kg				
Use	Use 1: furniture use				
	▪ Plastic accessories	9.1 kg	▪ CO ₂ ^a	2.1 kg	
	▪ Metallic accessories	15.7 kg	▪ CO ^a	0.003 kg	
	▪ Adhesives and glue	0.7 kg	▪ Particleboard solid waste	8.4 kg	
	▪ Diesel (particleboard distribution) ^a	0.7 kg	▪ Paint and varnish residues	0.7 kg	
	▪ Electricity	333.6 MJ	▪ Wardrobe	278.7 kg	
	▪ Particleboard	235 kg			
	▪ Cardboard	22.2 kg			
	▪ Paint and varnishes	4.8 kg			
	Use 2: wardrobe use				
	▪ Diesel (wardrobe distribution) ^a	4.9 kg	▪ CO ₂ ^a	14.8 kg	
			▪ CO ^a	0.03 kg	
	▪ Wardrobe	278.7 kg	▪ Cardboard waste	22.2 kg	
		▪ Wardrobe (end-of-life)	256.5 kg		
Post-use	Post-use				
	▪ Diesel (wardrobe final destination) ^a	0.8 kg	▪ CO ₂ ^a	2.6 kg	
			▪ CO ^b	3.3 kg	
	▪ Wardrobe (end-of-life)	256.5 kg	▪ Methane (CH ₄) ^b	4.9 kg	
		▪ CO ^a	0.004 kg		

^a Air emissions of CO₂ and CO due to diesel consumption

^b Air emissions of CO₂ and CH₄ due to particleboard decomposition in landfill

wood waste, so its contribution to the overall impacts of the wood supply chain would be (14.4 kg + 36.3 kg)/256.4 kg of wood. This assumption is important; otherwise, all impacts of the wood supply chain would be attributed only to *wood particle generation*, overestimating its environmental impacts. Likewise, impacts due the consumption of 26.7 kg

of urea-formaldehyde resin were also apportioned between the *blending and mat formation* unit process and the *hot-pressing* unit process, in order to share the resin impacts according to the associated manufacturing unit processes.

- In order to model the product system in Fig. 2 in the GaBi 6.5 software, some transport activities of raw materials were

Table 6 Indirect inventory flows of the particleboard life cycle

Description	Data source	Nation of origin
Steel sheet production (to produce metallic accessories)	GaBi software 6.5	Global
Diesel production mix at refinery	GaBi software 6.5	Brazil
Electricity mix supply chain	GaBi software 6.5	Brazil
Wood logs (eucalyptus species)	Silva et al. (2013)	Brazil
Wax/paraffin production at refinery	GaBi software 6.5	Brazil
Urea-formaldehyde resin production	Silva et al. (2015)	Brazil
Corrugated board boxes (cardboard) production	GaBi software 6.5	Europe
Polypropylene granulate production (to produce plastic accessories)	GaBi software 6.5	Europe
Ammonium sulfate (as catalyst) production	Ribeiro (2009)	Brazil
Water supply (to produce paints and varnishes)	GaBi software 6.5	Germany

included according to the transport distances assumed by Silva et al. (2013). The “GLO: Truck PE” process, Euro 3, with 27 t payload was chosen to represent most of the existing transport activities. As a result, a final consumption of 0.6 kg of diesel per functional unit was calculated.

For the product’s use phase, the following main considerations were made:

- To model product distribution from the particleboard company to the furniture assembler, the “GLO: Truck ELCD / PE-GaBi” process, Euro 3, and 12 t payload from the GaBi 6.5 software tool were selected. The transport distance was assumed to be 200 km. Thus, the total diesel consumption per functional unit was 0.7 kg.
- All input and output flows in Table 5 for *use 1* were extracted from Iritani et al. (2015). However, the original data of solid waste generation was changed from 29.9 to 8.4 kg for mass balance accuracy.
- *Use 2* was modeled assuming 1200 km for the wardrobe distribution phase in Brazil. This activity was modeled in the GaBi software using the “GLO: Truck ELCD/PE-GaBi” process, Euro 3, and with 12 t payload. The main destination of the studied product is the south region of Brazil, responsible for 60% of the wardrobe sales.
- *Use 2* also included the generation of 22 kg cardboard waste from the packaging process in *use 1*. For a 5-year product life, maintenance activities of the wardrobe must be based on its cleaning by only using a soft dry cloth and the use any liquids or solvents is no advisable. Thus, environmental aspects related to the wardrobe maintenance were not considered in the model.

Finally, regarding the post-use phase:

- In the end-of-life, it was assumed the final disposal of the wardrobe in a sanitary landfill located 100 km away from

the final consumer. This scenario was modeled based on estimates from the manufactured particleboard.

- In the “GLO: Truck PE” process, Euro 3 with 12 t payload was used as a reference for the transportation of the wardrobe to a landfill. For the distance of 100 km, a total diesel consumption of 0.8 kg per functional unit was calculated with the GaBi software tool.
- Particleboard decomposition in sanitary landfill was assumed using a landfill without biogas recovery (methane—CH₄), and CO₂ and CH₄ emissions were calculated from Micales and Skog (1997). Generation of CO₂ and CH₄ were, respectively, equivalent to 1.3% and 1.9% of the panel dry weight (Micales and Skog 1997).

2.4 Life cycle impact assessment and interpretation of results

The recommended ILCD v.1.06 method (European Commission/Joint Research Council/Institute for Environment and Sustainability, EC/JRC/IES, 2010) was used in an attributional approach and Fig. 4 shows the results of the LCIA. The focus was to analyze the overall LCA results for the cradle-to-grave life cycle of particleboards; after which, the LCA results are interpreted with focus on the manufacturing stage.

Thirteen midpoint impact categories were evaluated based on Klein et al. (2015) and Iritani et al. (2015): acidification, accumulated exceedance (AC); ecotoxicity for aquatic freshwater (EAF); freshwater eutrophication (FE); IPCC Global Warming, incl. biogenic carbon (GW); ionizing radiation (IR); marine eutrophication (ME); resource depletion, fossil and mineral (RD); ozone depletion (OD); particulate matter/respiratory inorganics (PM); photochemical ozone formation (POF); terrestrial eutrophication, accumulated exceedance (TE); human toxicity cancer effects, recommended (HTCE); and human toxicity non-canc. effects, recommended (HTNCE). LCIA results were also normalized

following the “PEF Pilot, incl. biogenic carbon [person equivalent]” factors available at the GaBi 6.5 software tool.

Results of Fig. 4 show that 81% of the impacts occurred for GW, RD, HTNCE, POF, AC, and HTCE. For these categories, the impacts were mainly due to the manufacturing phase of particleboards, use 1, and post-use. Hotspots in the particleboard manufacture were air emissions of free formaldehyde during the hot-pressing unit process; gaseous emissions of nitrogen oxides and sulfur dioxides, both from the urea-formaldehyde resin production and the wood production (forest operations driven by diesel-based machines); and GHG emissions due to the electricity supply chain and wood production. For use 1, the main hotspots were air emissions of heavy metals due to steel parts production used in the manufacture of metallic accessories of the wardrobe model and GHG emissions from the electricity supply chain. In the post-use, CH₄ releases from the panel decomposition in landfill were identified as the main hotspot.

Details of the main impacts for each manufacturing unit process are explained in Section 3.

3 Environmental hotspot analysis in particleboard manufacturing

Results in Fig. 5 point out that hot-pressing showed the greatest impact contributions followed by wood particles generation, and the blending and mat formation. It is also important to note that the sum of environmental impact percentages of all unit process from the particleboard manufacture represents 16.8% of the total life cycle impacts of the wardrobe.

However, results in Fig. 6 show that impacts were mostly due to direct impacts in the hot-pressing process. Figure 6 shows

that indirect impacts accounted for about 6% and they were due to upstream impacts of electricity and materials (wood, urea-formaldehyde resin, etc.) consumed at manufacture. Nevertheless, hot-pressing was responsible for 11.3% of the impacts as a result of airborne free formaldehyde emissions.

Based on the obtained results, it was clear that the hot-pressing process was the most prominent manufacturing process to be studied in-depth in order to verify the potential to reduce the particleboard’s upstream and downstream life cycle impacts at manufacture level. Therefore, the hot-pressing process was selected for the assessment of the green manufacturing scenarios described in Section 3.1.

3.1 Green manufacturing scenarios to reduce environmental hotspots

The hot-pressing process is a hydraulic pressing machine Marconi RA098/50AUSP model and its main components and subunits are presented in Fig. 7. The machine is a vertical hydraulic press composed of two plates (upper and lower plates), with maximum press capacity of 50 tons, maximum working temperature of 300 °C, a 200-V three-phase electrical supply, a pressing speed of 168 mm/min, and a total weight of 290 kg. The machine is located at the Wood and Timber Structures Laboratory (LaMEM) of the Department of Structural Engineering from the São Carlos School of Engineering (EESC), University of São Paulo (USP), Brazil.

The hydraulic press in Fig. 7 was selected because it shows the same basic operating parameters of a conventional machine used by particleboard companies, i.e., working pressure, pressure time, and temperature. However, its scale of production is for laboratory purposes.

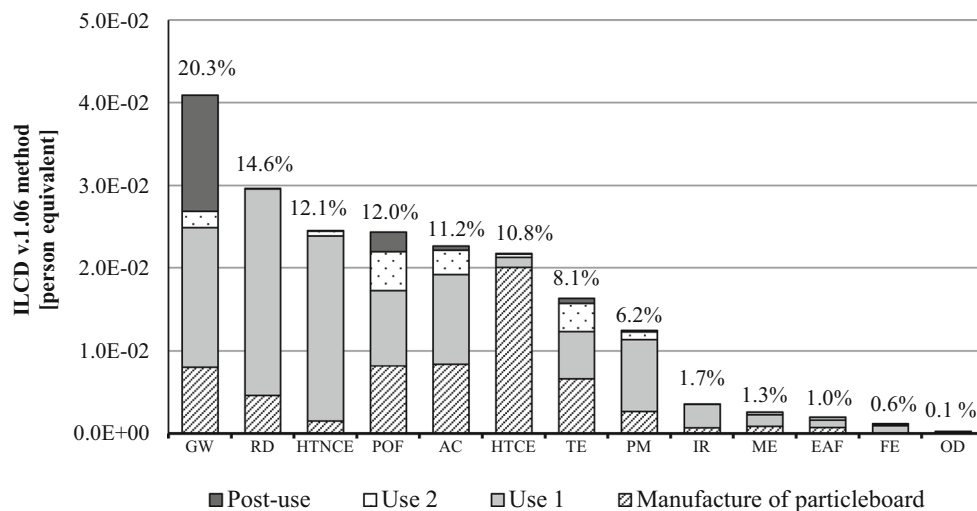


Fig. 4 Overall LCIA results. Acronyms: acidification, accumulated exceedance (AC); ecotoxicity for aquatic freshwater (EAF); freshwater eutrophication (FE); IPCC global warming, incl. biogenic carbon (GW); ionizing radiation (IR); marine eutrophication (ME); resource depletion, fossil and mineral (RD); ozone depletion (OD); particulate matter/

respiratory inorganics (PM); photochemical ozone formation (POF); terrestrial eutrophication, accumulated exceedance (TE); human toxicity cancer effects, recommended (HTCE); and human toxicity non-cancer effects, recommended (HTNCE)

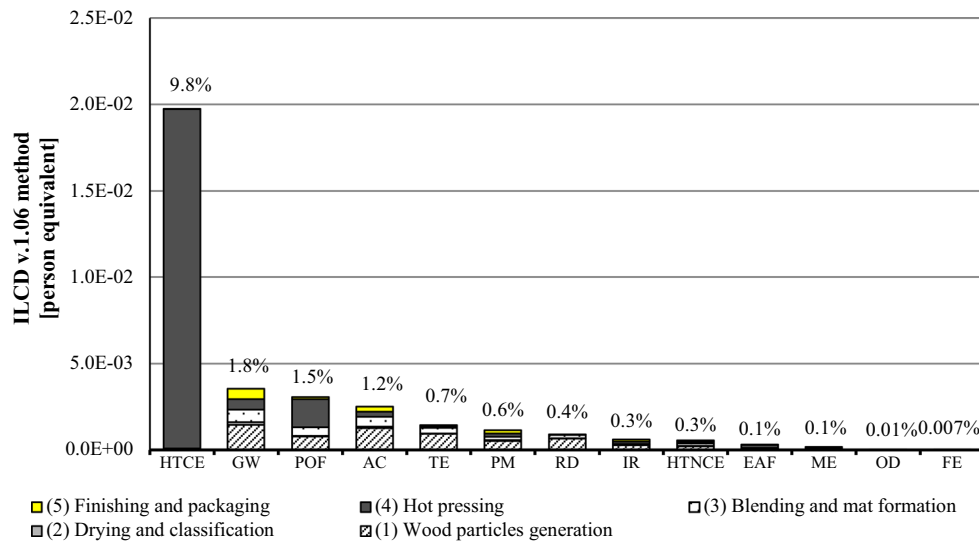


Fig. 5 LCIA results: manufacturing unit process contributions (not including the upstream and downstream life cycle stages). Acronyms: acidification, accumulated exceedance (AC); ecotoxicity for aquatic freshwater (EAF); freshwater eutrophication (FE); IPCC global warming, incl. biogenic carbon (GW); ionizing radiation (IR); marine

eutrophication (ME); resource depletion, fossil and mineral (RD); ozone depletion (OD); particulate matter/respiratory inorganics (PM); photochemical ozone formation (POF); terrestrial eutrophication, accumulated exceedance (TE); human toxicity cancer effects, recommended (HTCE); and human toxicity non-canc. effects, recommended (HTNCE)

For the selected hot-pressing machine, the system boundaries were set according to the UPLCI methodology application (Kellens et al. 2012a). Operation modes A (initiation), C (pressing), and D (standby) and three different subunits were investigated as illustrated in Fig. 8.

From analyzing Fig. 8, it is possible to check that the main environmental aspects to be monitored were electricity consumption and free formaldehyde air emissions, as they were the main environmental hotspots from the general LCA study. Indirect flows due to electricity consumption were included into the system boundaries from using the GaBi software tool.

Infrastructure flows due to the pressing machine construction were also included into the system boundaries modeling based on the tree diagram in Fig. 9.

In Fig. 9, the hydraulic pressing machine weighs 290 kg, and 230 kg are represented by the following materials and components: cast iron (125 kg), stainless steel (40 kg), hydraulic pump (45 kg), and hydraulic oil (20 kg). For these materials and components, the GaBi 6.5 software tool was used to include their respective indirect inventory flows of material production and manufacturing of components.

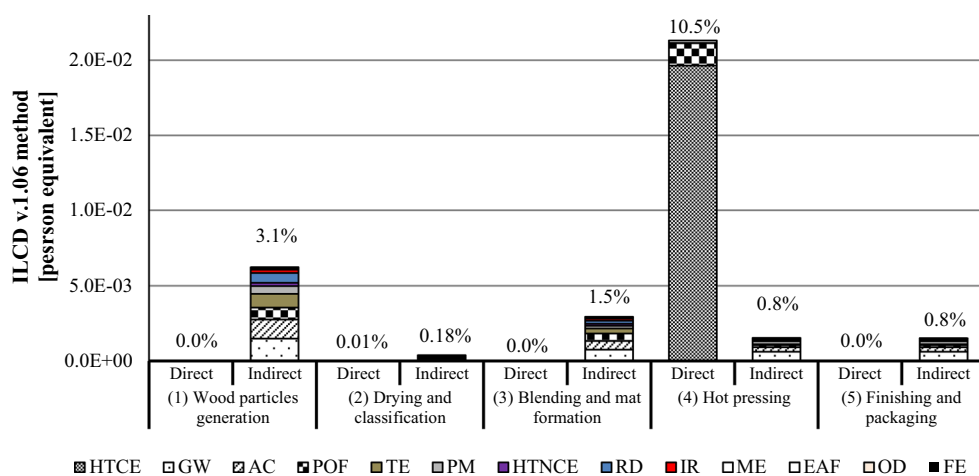


Fig. 6 LCIA results: direct and indirect manufacturing unit process contributions. Acronyms: acidification, accumulated exceedance (AC); ecotoxicity for aquatic freshwater (EAF); freshwater eutrophication (FE); IPCC global warming, incl. biogenic carbon (GW); ionizing radiation (IR); marine eutrophication (ME); resource depletion, fossil and

mineral (RD); ozone depletion (OD); particulate matter/respiratory inorganics (PM); photochemical ozone formation (POF); terrestrial eutrophication, accumulated exceedance (TE); human toxicity cancer effects, recommended (HTCE); and human toxicity non-canc. effects, recommended (HTNCE)

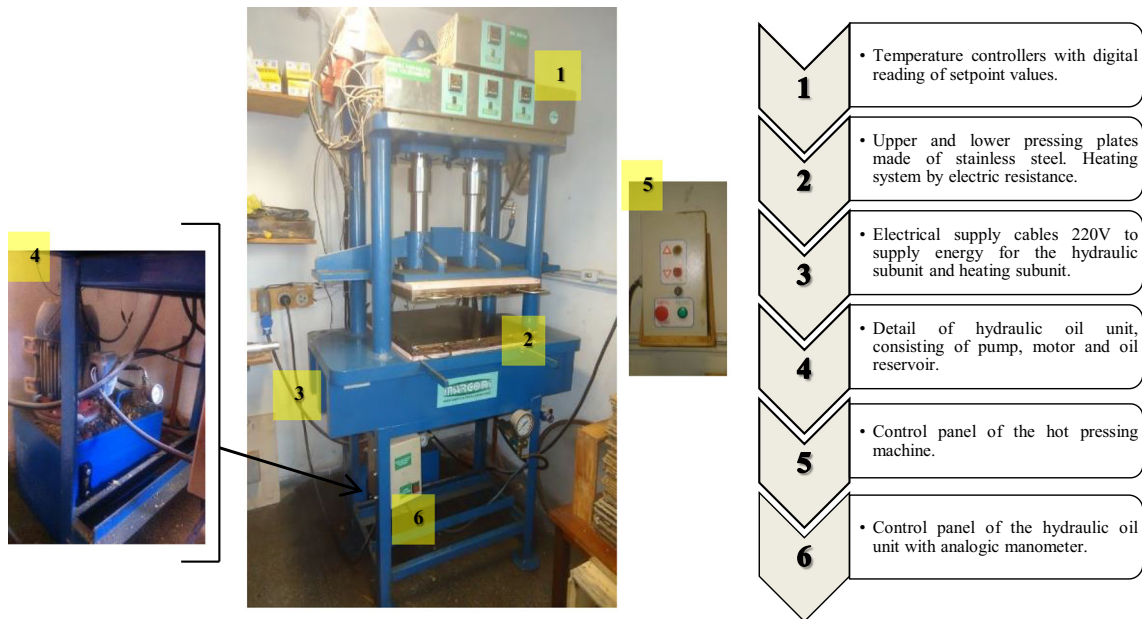
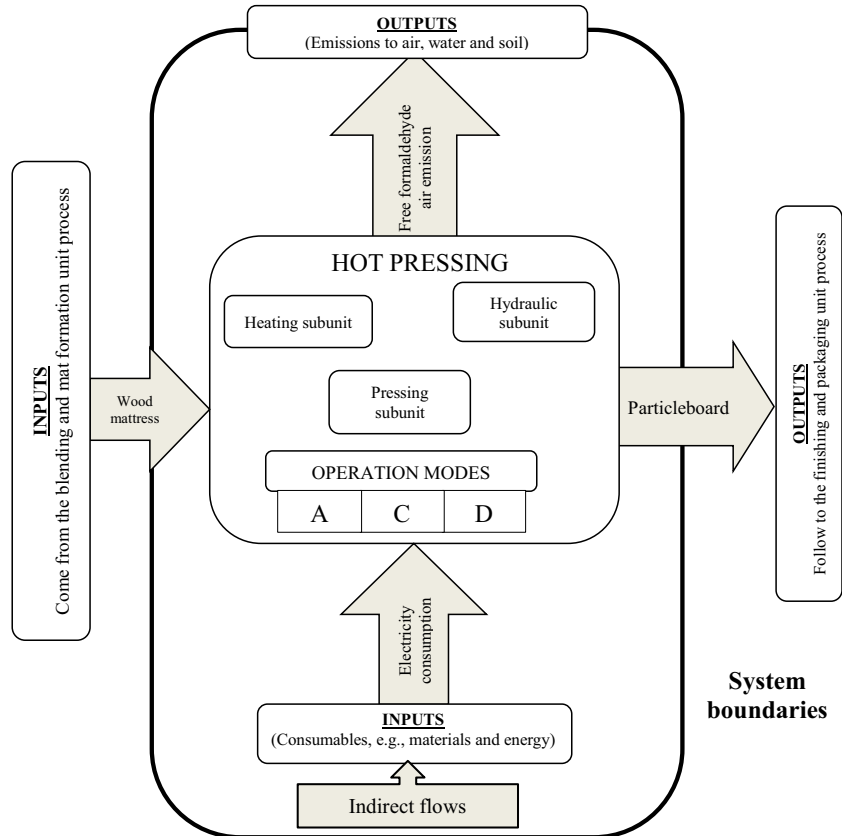


Fig. 7 Overview of the hot-pressing machine and its main components and subunits

An analysis of variance of the regression model was designed for the studied process and 12 manufacturing conditions were selected as shown in Table 7. This set of manufacturing scenarios was established from results of the case study data collection at the particleboard’s company.

Environmental monitoring of the hot-pressing was carried out and results showed that the consumption of electricity ranged from 1.16 to 2.00kWh for the reference flow of 235 kg of particleboards, while formaldehyde air emissions varied from 40.14 to 55.85 g over the different scenarios. Electricity consumption on the hot-pressing process was monitored according to the

Fig. 8 System boundaries of the hot-processing unit process



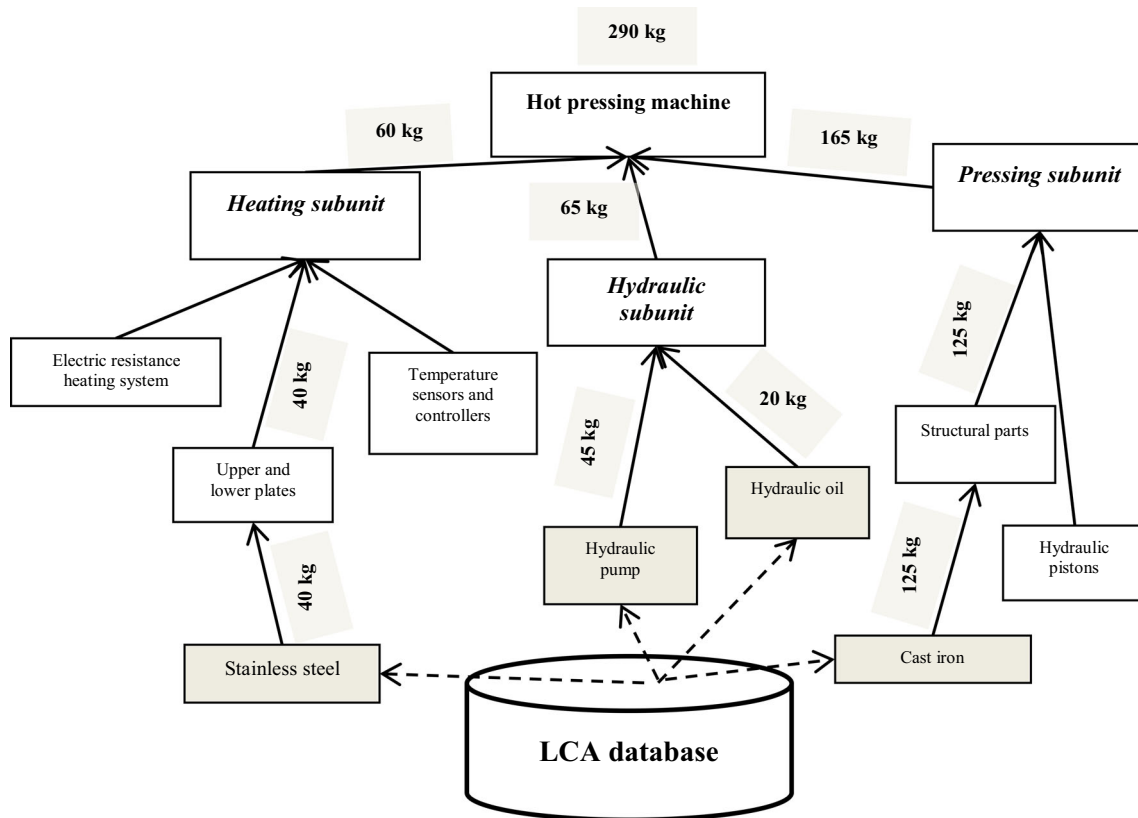


Fig. 9 Tree diagram for the hydraulic pressing machine

power study of the machine, following the UPLCI methodology. A digital ammeter Minipa ET-3200A with a precision of 0.01 A was installed at the hot-pressing power supply to measure current consumption. In order to monitor the air emissions of free formaldehyde, estimates were made as a function of the weight and moisture content of each particleboard produced based on the perforator method (EN 120 1992).

A total number of 36 particleboards were produced during the tests with the hot-pressing machine under the conditions presented in Table 7.

Figure 10 shows a profile of electricity power vs. time for the scenario with $P = 4$ MPa and $T = 160$ °C. Other equivalent curves were found for the remaining 11 manufacturing conditions as well. Although the power consumed in the initiation mode is greater than in other operation modes, it is important to note that the initiation mode occurs only once a day. The heating, hydraulic, and pressing subunits can be seen in Fig. 10 and they are all activated when the pressing mode is working. Initiation mode (or start-up) lasts more than 1 h due to the slow process of heating the press machine, while the pressing mode lasts approximately 10 min, and standby mode takes about 5 min before and after each pressing process.

In this sense, Fig. 11 shows a scenario analysis to reduce the life cycle environmental hotspots with focus on GW impacts because it was one of the most representative impact categories according to the normalized impacts in Figs. 4

and 5. The reference scenario was 3 MPa; 160 °C and the following alternatives were drawn:

- *Scenario 1*: reduction of the particleboard density up to 0.53 g/cm^3 ;
- *Scenario 2*: reduction of the pressing heating time by 10%.

Scenario 1 was important as the higher the particleboard nominal densities are, the higher the GW impacts, because of the higher energy requirements for the hot-pressing process. For each of the 36 manufactured particleboards, the densities were quantified varying from 530 to 790 kg/m^3 . According to the literature indicated in Table 1, the density of particleboards can vary from 500 to 800 kg/m^3 , and this parameter can directly affect the wood consumption (Santos et al. 2014; Silva et al. 2014). Scenario 2 was defined based on the results from Fig. 10, as high idle times can be observed and, therefore, this scenario could eliminate part of the wasted energy by adopting faster setup activities.

Figure 11 also presents a combined scenario based on results of scenarios 1 and 2. In addition, the 4.5 MPa; 170 °C scenario, which refers to the situation with the highest results of environmental impacts, is included. Thus, it is possible to verify a potential reduction of upstream impacts for GW by up to 21% (raw materials supply) and up to 41% in the post-use

Table 7 Manufacturing conditions for environmental monitoring at the hot-pressing unit process

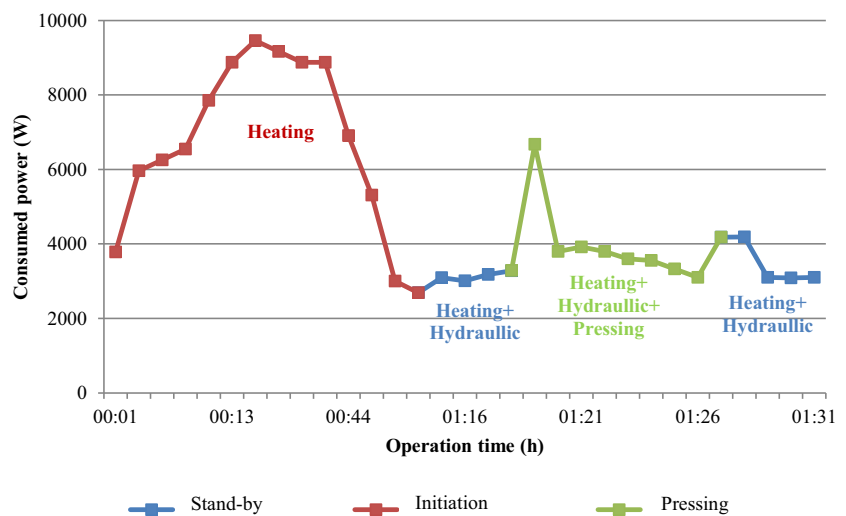
Process parameter	Unit	Minimum value	...	Maximum value
Temperature (<i>T</i>)	°C	160	165	170
Pressure (<i>P</i>)	MPa	3	3.5 4.0	4.5
Condition	Combination of <i>P</i> and <i>T</i>			
<i>P</i> × <i>T</i> : 1	<i>P</i> = 3 MPa; <i>T</i> = 160 °C			
<i>P</i> × <i>T</i> : 2	<i>P</i> = 3 MPa; <i>T</i> = 165 °C			
<i>P</i> × <i>T</i> : 3	<i>P</i> = 3 MPa; <i>T</i> = 170 °C			
<i>P</i> × <i>T</i> : 4	<i>P</i> = 3.5 MPa; <i>T</i> = 160 °C			
<i>P</i> × <i>T</i> : 5	<i>P</i> = 3.5 MPa; <i>T</i> = 165 °C			
<i>P</i> × <i>T</i> : 6	<i>P</i> = 3.5 MPa; <i>T</i> = 170 °C			
<i>P</i> × <i>T</i> : 7	<i>P</i> = 4.0 MPa; <i>T</i> = 160 °C			
<i>P</i> × <i>T</i> : 8	<i>P</i> = 4.0 MPa; <i>T</i> = 165 °C			
<i>P</i> × <i>T</i> : 9	<i>P</i> = 4.0 MPa; <i>T</i> = 170 °C			
<i>P</i> × <i>T</i> : 10	<i>P</i> = 4.5 MPa; <i>T</i> = 160 °C			
<i>P</i> × <i>T</i> : 11	<i>P</i> = 4.5 MPa; <i>T</i> = 165 °C			
<i>P</i> × <i>T</i> : 12	<i>P</i> = 4.5 MPa; <i>T</i> = 170 °C			

for the manufacturing condition 3 MPa; 160 °C—combined with scenarios 1 and 2.

3.2 Green manufacturing indicators for the hot-pressing machine

Life cycle performance indicators for the evaluated hot-pressing machine were defined based on the hot-pressing parameters. The use of regression models for the definition of environmental performance indicators can be advantageous since such models are statistically developed and adjusted based on experimental results of the process monitoring. Additionally, it is also possible to know the reliability level of the models based on *R*² coefficients of determination. Individual models should be developed for each impact category under interest.

Fig. 10 Electricity consumption profile of the hot-pressing unit process: 4 MPa and 160 °C



For this, a regression model was delineated and tested using variance statistic analysis (see Table 8). The indicators were generated for the GW impact category.

From Table 8, results are explained in large part by the *P*² parameter. It should be noted that the complete quadratic model was considered significant by ANOVA and the adjusted *R*² coefficient was 86.7%. The regression model is expressed in Eq. 1.

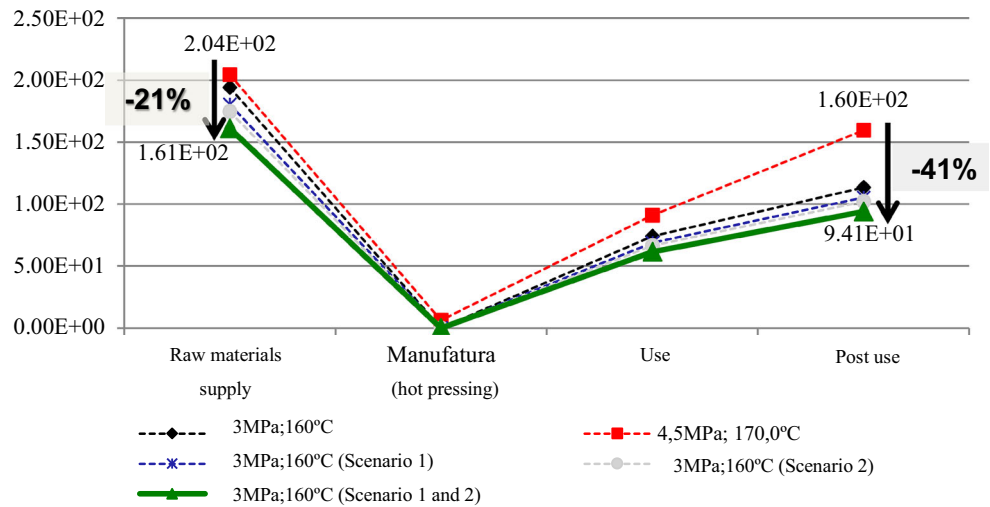
$$GW = -4101.06 + 42.24P + 49.88 T - 1.1333P \times T + 25.78P^2 - 0.13T^2 \tag{1}$$

From Eq. 1, it is possible to determine life cycle impacts of particleboards based on the hot-pressing main parameters, *P* and *T*. As GW impacts are explained basically by the square of pressure values, it is possible to obtain a simpler model expressed by Eq. 2. To do so, a new regression model was generated in the determination of GW impacts as a function of *P*² values only. Such adjustment was considered significant by ANOVA (*p* value = 0.000), with a coefficient of determination equal to 71.80%.

$$GW = 322 + 6.55P^2 \tag{2}$$

The optimum solution of Eq. 2 consists of assuming *P* = 0; however, that is not possible due to the problem domain (3 MPa ≤ *P* ≤ 4.5 MPa). As GW increases with *P* > 0, *P* values should be 3 MPa, as expected. It is also interesting to note the dependence of GW on the pressure values. Hence, if the pressing pressure is known, it is possible to estimate GW impacts for the whole particleboards' life cycle. Equation 2 is an important result to promote green manufacturing at the company studied, since it should better control its environmental performance for GW impacts. This strategy gives attention on monitoring the environmental impact category instead of

Fig. 11 Scenario analysis to reduce environmental hotspots—GW (kg CO₂-eq.)



monitoring environmental aspects that could not be related to the life cycle hotspot analysis.

4 Conclusions

The use of LCA is a relevant tool towards green manufacturing and a case study was used within this paper to investigate GM alternatives to produce particleboards in Brazil. The topic of LCA + GM has been growing in terms of number of publications and interest by the LCA community; however, few initiatives evaluate this topic in the wood sector.

Most of the available LCA + GM studies still do not look at the effect of manufacture of products into upstream and downstream life cycle impacts and this paper showed a detailed analysis of that based on the particleboard production disaggregation into unit process level. LCIA was performed based on the ILCD recommendation method and its 13 midpoint impact categories and normalization factors. Each of the five manufacturing unit processes was investigated and it was found that the overall contribution of the manufacture phase represented 16.8% of the particleboard life cycle impacts. However, those impacts were mostly due to direct impacts in the hot-pressing process (11.3%) because of airborne free formaldehyde emissions and

on-site electricity consumption. Most of the hot-pressing impacts are attributed to the GW impact category.

A detailed analysis of the hot-pressing process was designed based on ANOVA and the UPLCI methodology application. In total, 12 manufacturing conditions were set up based on varying temperature and pressing parameters of the hydraulic press machine. Thirty-six particleboards were manufactured at the hot-pressing machine under investigation and some green manufacturing scenarios were defined.

It was found that up to 41% of the environmental impacts for GW can be avoided by the introduction of simple manufacturing changes, such as the reduction of idle times of the hot-pressing unit process and by minimizing the panel density up to 0.53 g/cm³. Such suggestions described in section 3.1 are technically feasible and the studied company was interested in putting them into practice in the near future.

Other improvements in the particleboard industry should focus on reducing free formaldehyde emissions at the hot-pressing process. Urea-formaldehyde resin should be replaced by alternative resins, for example, resins from renewable sources. However, such improvement opportunities were not evaluated on this paper.

Some green manufacturing indicators for the hot-pressing monitoring were established based on regression models and results showed that GW impacts are basically attributed to the press parameter. A simplified version of the model was adjusted with *R*² coefficient = 71.80%. The developed indicator should be used by particleboard companies to predict particleboard’s GW life cycle impacts. The evaluated model can be adjusted to predict other environmental impacts for different impact categories as in literature most of the GM studies still focus only on the monitoring of environmental aspects based on resource consumption and emissions in manufacturing.

Finally, the proposed GM framework can be used in other case studies to integrate GM + LCA in practice. The framework can be adapted for other case studies in order to properly investigate life cycle impacts from a greener manufacturing perspective.

Table 8 Results of the quadratic regression models for GM impacts

Process parameters	<i>P</i> values for GW
<i>P</i>	0.805
<i>T</i>	0.418
<i>P</i> × <i>T</i>	0.241
<i>P</i> ²	0.006
<i>T</i> ²	0.484
<i>c</i> ^{te}	0.421
Regression	0.000
<i>R</i> ²	86.67%

APPENDIX I – Case study questionnaire

Part 1: Identification of the visited company

Date: _____
 Company: _____ State: _____ City: _____
 Address: _____
 People for contact/interviewees: _____
 Produced products: _____
 Annual production of products: _____

Part 2: List of general questions for the selected company and product of interest

1. Have any previous LCA studies been done by/for the company? *If yes, request a copy of it.*
 2. Provide a Process Flow Diagram of the manufacture processes for the product of interest.
 3. What are the main technologies applied in the production process based on the Process Flow Diagram in Question 2? *Describe machines and industrial equipment details, recycling/recovery processes, etc.*
 4. Product specification
 - a) Technical description of the selected product and its main function. *Product's Tree Diagram and/or Bill of Materials can be used in this process as well as a product's user manual or its instructions for use.*
 - b) List product's quality requirements for the product of interest, i.e., make a list of its main physical, mechanical, and chemical properties.
 5. Based on the product's function, define a Functional Unit (UF) and a Reference Flow (RF) according to the LCA standards ISO 14040 and 14044.
 6. How do the distribution, use, and end-of-life of the selected product occur after manufacture?
 - a) **Distribution:** Describe logistical aspects from the manufacture gate to the consumer gate (type of vehicles, distances, type of fuel, vehicles specification, etc.). Use the template model below:

Description of inputs for transportation	Transport system details (vehicle, payload, fuel):		Return empty? (yes/no)
	Distance (km)	Cargo (ton)	

- b) **Use:** What is the product's useful life? Which are the main maintenance activities during the product's use phase? *Make a list of relevant environmental aspects at the product's use phase.*
- c) **End-of-life:** Which strategies of end-of-life are applied to the product of interest? What is the predominant strategy? *Make a list of relevant environmental aspects at the product's post-use phase.*

Part 3: List of questions about the main inputs and raw materials

7. Which inputs and raw materials are consumed during the product manufacture?
 - a) Provide an organized list with values of each flow adjusted for the reference flow defined in Part 2.
 - b) Provide additional information about average values of the inputs and raw materials' main properties (chemical, physical, and mechanical properties), if necessary.
 - c) Describe how inputs and raw materials are transported to the factory. Use the same template from Question 6a.
8. What is the energy demand for the manufacture process defined in Question 2, as well as for the factory facilities? Which types of energy are consumed (e.g., biomass, oil, gas) and how are they internally managed by the company?
9. Which are the main emissions and waste generated during the product manufacture?
 - a) Provide an organized list with the values of each flow adjusted for the reference flow defined in Part 2.
 - b) Provide additional information about average values of the outputs main properties (chemical, physical, and mechanical properties), if necessary.

c) Describe how solid waste and emissions are transported from the factory to the final disposition (e.g., landfill, incineration, recovery). Use the same template from Question 6a.

10. What is the reference year for the collected data from Questions 1 to 9?

11. Provide a list of the main limitations and assumptions for the collected data from Questions 1 to 10.

Part 4: List of questions about the selected manufacturing process of interest

12. Description of the manufacturing unit process of interest:

13. Which process parameters are used to control the manufacturing process of interest? *Specify average values and maximum and minimum tolerated values for each process parameter.*

14. Based on Question 4b, which product quality requirements are most important for the manufacturing process of interest? How can the manufacturing process affect the product's quality requirements?

15. Specify operation modes and machine subunits for the selected manufacturing unit process.

16. What is the time of operation for the selected manufacturing process to produce one unit of the studied product? Stratify this time in level of operation modes and machine subunits too.

Acknowledgments The authors are grateful for the financial support provided by two Brazilian Governmental Funding Agencies: Coordination for the Improvement of Higher Education Personnel (“Coordenação de Aperfeiçoamento de Pessoal de Nível Superior,” CAPES—9331/13-1) and São Paulo Research Foundation (“Fundação de Amparo à Pesquisa do Estado de São Paulo,” 2013/06736-9). Diogo A. Lopes Silva is also grateful for the financial support provided by the 2017 LCA Awards of the Life Cycle Initiative.

References

- Araujo JB, Oliveira JFG (2012) Towards a balanced scoreboard for assessing manufacturing processes sustainability. *Int J Bus Perform Manag* 13:198–221. <https://doi.org/10.1504/IJBPM.2012.046201>
- Aurich JC, Linke B, Hauschild M, Carrella M, Kirsch B (2013) Sustainability of abrasive processes. *CIRP Ann Manuf Technol* 62:653–672. <https://doi.org/10.1016/j.cirp.2013.05.010>
- Chompu-inwai et al (2015) A combination of material flow cost accounting and design of experiments techniques in an SME: the case of a wood products manufacturing company in northern Thailand. *J Clean Prod* 108:1352–1364. <https://doi.org/10.1016/j.jclepro.2014.08.039>
- Dornfeld DA (2014) Moving towards green and sustainable manufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology* v1:63–66. doi: <https://doi.org/10.1007/s40684-014-0010-7>
- EN 120 (1992) Wood based panels—determination of formaldehyde content—extraction method called the perforator method
- European Commission/Joint Research Council/Institute for Environment and Sustainability (2010) International reference life cycle data system (ILCD) handbook: framework and requirements for LCIA models and indicators. Luxembourg: European Commission. Joint Research Council. Institute for Environment and Sustainability, 2010, EC/JRC/IES
- Ferro FS, Silva DAL, Argenton M, González-García S (2018a) Environmental aspects of oriented strand boards production. A Brazilian case study. *J Clean Prod* 183:710–719. <https://doi.org/10.1016/j.jclepro.2018.02.174>
- Ferro FS, Silva DAL, Icimoto FH, Lahr FAR, González-García S (2018b) Environmental life cycle assessment of industrial pine roundwood production in Brazilian forests. *Sci Total Environ* 640–641:599–608. <https://doi.org/10.1016/j.scitotenv.2018.05.262>
- Filleti RAP, Silva DAL, Silva EJ, Ometto AR (2014) Dynamic system for life cycle inventory and impact assessment of manufacturing processes. *Proc CIRP* 15:531–536. <https://doi.org/10.1016/j.procir.2014.06.024>
- Filleti RAP, Silva DAL, Silva EJ, Ometto AR (2017) Productive and environmental performance indicators analysis by a combined LCA hybrid model and real-time manufacturing process monitoring: a grinding unit process application. *J Clean Prod* 161:510–523. <https://doi.org/10.1016/j.jclepro.2017.05.158>
- Florida R (1996) Lean and green: the move to environmentally conscious manufacturing. *Calif Manag Rev* 39:80–105
- Garcia R, Freire F (2014) Carbon footprint of particleboard: a comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. *J Clean Prod* 66:199–209. <https://doi.org/10.1016/j.jclepro.2013.11.073>
- Garretti M, Taisch M (2012) Sustainable manufacturing: trends and research challenges. *Prod Plan Control* 23:83–104. <https://doi.org/10.1080/09537287.2011.591619>
- Gloria TP, Kohlsaas C, Bautil P, Wolf B, Early D, Ben-Zekry B (2014) A statistical approach to interpret relative environmental performance within product categories. *Int J Life Cycle Assess* 19:491–499. <https://doi.org/10.1007/s11367-013-0661-6>
- Igos E, Benetto E, Meyer R, Baustert P, Othoniel B (2019) How to treat uncertainties in life cycle assessment studies? *Int J Life Cycle Assess* 24:794–807. <https://doi.org/10.1007/s11367-018-1477-1>
- International Organization of Standardization (2006a) ISO 14040: environmental management—life cycle assessment—principles and framework. Geneva, ISO
- International Organization of Standardization (2006b) ISO 14044: Environmental management—life cycle assessment—requirements and guidelines. Geneva, ISO
- Iritani DR, Silva DAL, Saavedra YMB, Grael PFF, Ometto AR (2015) Sustainable strategies analysis through life cycle assessment: a case study in a furniture industry. *J Clean Prod* 96:308–318. <https://doi.org/10.1016/j.jclepro.2014.05.029>
- Jeswiet J, Kara S (2008) Carbon emissions and CEST™ in manufacturing. *CIRP Ann Manuf Technol* 57:17–20. <https://doi.org/10.1016/j.cirp.2008.03.117>
- Jiang Z, Zhang H, Sutherland J (2012) Development of an environmental performance assessment method for manufacturing process plans. *Int J Adv Manuf Technol* 58:783–790. <https://doi.org/10.1007/s00170-011-3410-7>
- Jin Y, Noh SD (2014) Stochastic model-based framework for assessment of sustainable manufacturing technology. *Int J Prec Eng Manuf* 15: 519–525. <https://doi.org/10.1007/s12541-014-0366-1>
- Joung CB et al (2012) Categorization of indicators for sustainable manufacturing. *Ecol Indic* 24:148–157. <https://doi.org/10.1016/j.ecolind.2012.05.030>
- Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR (2012a) Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 1: methodology description. *Int J Life Cycle Assess* 17:69–78. <https://doi.org/10.1007/s11367-011-0340-4>
- Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR (2012b) Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies. *Int J Life Cycle Assess* 17:242–251. <https://doi.org/10.1007/s11367-011-0352-0>
- Kellens K, Baumers M, Gutowski TG, Flanagan W, Lifset R, Duflou JR (2017a) Environmental dimensions of additive manufacturing: mapping application domains and their environmental implications. *J Ind Ecol* 21:49–68. <https://doi.org/10.1111/jiec.12629>
- Kellens K, Mertens R, Paraskevas D, Dewulf W, Duflou JR (2017b) Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of part manufacturing? *Proc CIRP* 61:582–587. <https://doi.org/10.1016/j.procir.2016.11.153>
- Kim DB, Shin SJ, Shao G, Brodsky A (2015) A decision-guidance framework for sustainability performance analysis of manufacturing processes. *Int J Adv Manuf Technol* 78:1455–1471. <https://doi.org/10.1007/s00170-014-6711-9>
- Klein D, Wolf C, Schulz C, Weber-Blaschke G (2015) 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. *Int J Life Cycle Assess* 20:556–575. <https://doi.org/10.1007/s11367-015-0847-1>
- Kouchaki-Penchah H, Sharifi M, Mousazadeh H, Zarea-Hosseinabadi H, Nabavi-Pelesaerai A (2016) Gate to gate life cycle assessment of flat pressed particleboard production in Islamic Republic of Iran. *J Clean Prod* 112:343–350. <https://doi.org/10.1016/j.jclepro.2015.07.056>
- Li W (2015) Efficiency of manufacturing processes. In: Herrmann C, Kara S (eds) Sustainable production, life cycle engineering and management. Springer, Switzerland, pp 5–22

- Li C et al (2010a) AHP based SWOT analysis for green manufacturing strategy selection. *Key Eng Mat* 431(432):249–252. <https://doi.org/10.4028/www.scientific.net/KEM.431-432.249>
- Li C, Liu F, Tan X, du Y (2010b) A methodology for selecting a green technology portfolio based on synergy. *Int J Prod Res* 48:7289–7302. <https://doi.org/10.1080/00207540903382857>
- Linke B, Overcash M (2012) Life cycle analysis of grinding. In: Dornfeld DA, Linke BS (eds) *Leveraging technology for a sustainable world*. Springer, Berkeley, pp 293–298
- Micales, J.A.; Skog, K.E.(1997) The Decomposition of forest products in landfills. *International Biodeterioration and Biodegradation*, v.39, n.2/3, p.145-158, 1997
- Montgomery DC (2008) *Design and analysis of experiments.*, 7rd edn. Wiley, New York
- Nakano K et al (2018) Life cycle assessment of wood-based boards produced in Japan and impact of formaldehyde emissions during the use stage. *Int J Life Cycle Assess* 23:957–969. <https://doi.org/10.1007/s11367-017-1343-6>
- Ribeiro PH (2009) Contribuição ao banco de dados brasileiro para apoio à avaliação do ciclo de vida: fertilizantes nitrogenados. Thesis, University of São Paulo
- Rivela B, Hospido A, Moreira T, Feijoo G (2006) Life cycle inventory of particleboard: a case study in the wood sector. *Int J Life Cycle Assess* 11:106–113. <https://doi.org/10.1065/lca2005.05.206>
- Santos MFN et al (2014) Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (*Saccharum spp.*) and pine wood shavings (*Pinus Eçlliottii*). *J Clean Prod* 64:345–355. <https://doi.org/10.1016/j.jclepro.2013.06.039>
- Shin S-J et al. (2015) Process-oriented life cycle assessment framework for environmentally conscious manufacturing. *J Intell Manuf* 1–19. <https://doi.org/10.1007/s10845-015-1062-4>
- Silva DAL, Lahr FAR, Garcia RP, Freire FMCS, Ometto AR (2013) Life cycle assessment of medium density particleboard (MDP) produced in Brazil. *Int J Life Cycle Assess* 18:1404–1411. <https://doi.org/10.1007/s11367-013-0583-3>
- Silva DAL, Lahr FAR, Pavan ALR, Saavedra YMB, Mendes NC, Sousa SR, Sanches R, Ometto AR (2014) Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing. *Int J Life Cycle Assess* 9:1767–1778. <https://doi.org/10.1007/s11367-014-0776-4>
- Silva DAL, Filleti RAP, Christoforo AL, Silva EJ, Ometto AR (2015) Application of life cycle assessment (LCA) and design of experiments (DOE) to the monitoring and control of a grinding process. *Proc CIRP* 29:508–513. <https://doi.org/10.1016/j.procir.2015.01.037>
- Silva DAL, Ometto AR, Silva EJ (2016) Green manufacturing: uma análise da produção científica e de tendências para o futuro. *Production* 26:642–655. <https://doi.org/10.1590/0103-6513.032513>
- Silva DAL et al (2018) Life cycle assessment in automotive sector: a case study for engine valves towards cleaner production. *J Clean Prod* 184:286–300. <https://doi.org/10.1016/j.jclepro.2018.02.252>
- Singh A, Philip D, Ramkumar J (2015) Quantifying green manufacturability of a unit production process using simulation. *Proc CIRP* 29: 257–262. <https://doi.org/10.1016/j.procir.2015.01.034>
- Vikhorev K, Greenough R, Brown N (2013) An advanced energy management framework to promote energy awareness. *J Clean Prod* 43: 103–112. <https://doi.org/10.1016/j.jclepro.2012.12.012>
- Weber C, Iwakiri S (2015) Utilization of waste of plywood, MDF and MDP for the production of particleboards. *Ciência Florestal* 25:405–413. <https://doi.org/10.5902/1980509818460>
- Wilson JB (2008) Particleboard: a life-cycle inventory of manufacturing panels from resource through product. Phase II final report. Consortium for Research on Renewable Industrial Materials. May CORRIM, Inc. University of Washington, Seattle, WA, 58
- Wilson JB (2010) Life-cycle inventory of particleboard in terms of resources, emissions, energy and carbon. *Wood Fiber Sci* 42:90–106
- Yin RK (2015) *Case study research: design and methods (applied social research methods)*, 5th edn. SAGE Publications, Inc, Thousand
- Zendoia J, Woy U, Ridgway N, Pajula T, Unamuno G, Olaizola A, Fysikopoulos A, Krain R (2014) A specific method for the life cycle inventory of machine tools and its demonstration with two manufacturing case studies. *J Clean Prod* 78:139–151. <https://doi.org/10.1016/j.jclepro.2014.05.012>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.