Journal of Cleaner Production 96 (2015) 308–318

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Sustainable strategies analysis through Life Cycle Assessment: a case study in a furniture industry

D.R. Iritani [a, *], D.A.L. Silva [a], Y.M.B. Saavedra [b], P.F.F. Grael [a], A.R. Ometto [a, b]

[a] Department of Production Engineering, São Carlos School of Engineering, University of São Paulo, 400 Trabalhador São-Carlense Avenue, São Carlos 13566-590, Brazil

[b] Environmental Engineering Sciences, São Carlos School of Engineering, University of São Paulo, 400 Trabalhador São-Carlense Avenue, São Carlos 13566-590, Brazil

ARTICLE INFO

Article history:
Received 26 September 2013
Received in revised form
10 April 2014
Accepted 8 May 2014
Available online 17 May 2014

Keywords:
Life Cycle Assessment (LCA)
Environmental performance
Sustainability
Medium density particleboard(MDP)
Environmental impact
Sustainable strategy

ABSTRACT

This article aims to analyze sustainable strategies by assessing the environmental performance of a wardrobe built from medium density particleboard. For this, the Life cycle assessment technique was used. The product life cycle studied was a cradle-to-gate type, including three main stages: raw materials supply, wardrobe manufacturing and distribution of the wardrobe. The functional unit was 40 kg of stored goods/5 years and the reference flow was one wardrobe unit. The LCA modeling process was undertaken using the GaBi software, Professional 4.4 version based on attributional modeling and the EDIP-97 method. The life cycle assessment results indicated that the most significant environmental impacts occur at the stages of raw materials supply and the distribution of the wardrobe, and the most relevant impact categories were human toxicity, global warming and acidification, totaling 68.0% of the overall life cycle impacts. Based on this results and a literature review of life cycle assessment studies of furniture products, two sustainable strategies were presented: to optimize transport system and the use of alternatives raw materials during the manufacturing of medium density particleboard. In addition, three scenarios for the production of the medium density particleboard were analyzed with focus on using recycled wood as raw material instead of virgin wood. The results showed that use of 100% wood waste was more sustainable because there was a global minimization of potential impacts. These conclusions can assist furniture and the wood-based panel industries in improving their environmental profile and encourage research about alternative options to promote cleaner production of furniture components in a life cycle perspective.

1. Introduction

Sustainable strategies comprise a set of activities aimed at improving environmental, economic and social aspects of business processes and products, enabling stakeholders to make the right choices and the best decisions. However, the challenge is to select the most appropriate strategy for each case under study (Chen et al., 2012). Accordingly, a method that may assist in this challenge is the Life Cycle Assessment (LCA). LCA arose from the growing awareness of environmental protection and the impacts caused by products (goods and services), keeping in mind where the impacts are really significant, taking into account the whole life cycle (ISO, 2006a,b).

A number of studies have focused on the application of LCA to a wide range of products in recent years. Schweinle (2007) draws attention to LCA studies for wood-based products, focusing mainly on issues such as: carbon footprint, bioenergy generation systems and life cycle engineering of new and innovative products based on renewable resources. Thus, outlining these issues allows a better understanding of the relevant environmental hotspots when working with such products.

According to the Brazilian Association of Forests Planted Producers (ABRAF, 2013), in 2012, the forest base totaled BRL 56.3 billion (Brazilian Reals), 4.6% higher than 2011. Moreover, the sector's activities contributed to the generation of 4.4 million jobs and an investment of BRL 149.0 million in social inclusion, education and the environmental programs. In 2012, 35.2% of the total forest

* Corresponding author. Tel.: +55 16 33738206.
E-mail addresses: diritani@yahoo.com.br, diritan@gmail.com (D. Iritani).

http://dx.doi.org/10.1016/j.jclepro.2014.05.029
0959-6526/

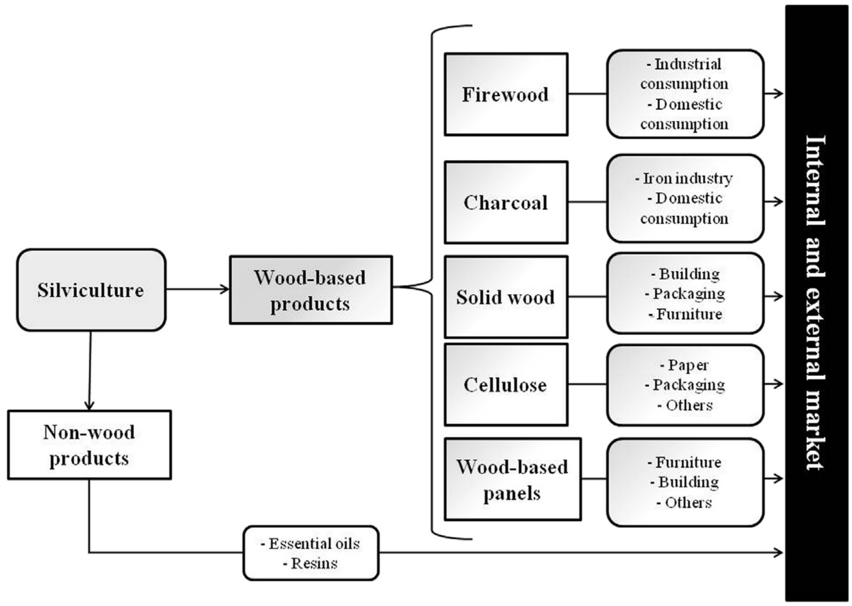


Fig. 1. Basic applications of wood – adapted from ABRAF (2013).

planted wood was used for the production of cellulose, 7.1% in the production of panels, 16.4% in sawn timber and 2.7% in the production of plywood. The remaining 38.6% was used to produce charcoal, firewood and other forest products (ABRAF, 2013). The main products of the forest-based sector can be schematically represented in Fig. 1.

Among the basic applications for wood, Biazus et al. (2010) highlighted the wood-based panels sector, which in Brazil is very dynamic and competitive, due to the quality and wide acceptance of products in the market. Approximately 98.6% of wood-based panels in Brazil are destined for the internal market and 1.4% for the external market. According to ABRAF (2013), the market for wood panels has grown from 3.1 million tons to 7.3 million in the last 10 years (2002–2012), an average growth of 8.9% per year. Moreover, between 2010 and 2014 the expected investments are of U.S. $1.2 billion in the panel industry (Brazilian Association of the Wood Panels Industry – ABIPA, 2014), which will take today's installed panel capacity of 10.3–10.9 million cubic meters per year. The Brazilian wood panel industry features in the list of the world's ten largest producers, ranking 6th in 2008 (Biazus et al., 2010).

According to Thoemen et al. (2010), the main types of wood panels can be classified into:

- *Solid wood*: also referred to as mechanically processed wood, this segment is mainly represented by plywood, a kind of panel formed by bonded layers which is light weight and has good mechanical strength. This group can also include laminated veneer lumber (LVL) and glued laminated timber (GLT), widely used in the construction industries;
- *Reconstituted*: consist of industrialized wooden panels made with particles or fibers, and the main products being: particleboards/medium density particleboard (MDP), oriented strand board (OSB), medium density fiberboard (MDF), hard density fiberboard (HDF). This category also encompasses other less used composite materials, such as wood-cement, wood-plastic and other lignocellulosic materials.

Considering the existing main types of wood panels, Table 1 gives a summary of the main LCA studies of these products between 2003 and 2013.[1]

The United States appears with the largest number of articles, and this is mainly due to the Consortium for Research on Renewable Industrial Materials (CORRIM), which since the last decade has inventoried many wood-based products with emphasis on wood panels (Puettmann et al., 2010). Regarding the objective of these articles, most include LCA case studies focusing on the life cycle inventory, identifying hotspots and suggesting environmental improvements to the product's life cycle.

Most of publications in Table 1 are focused on reconstituted panels (i.e., MDP, MDF, OSB, HDF) and this can be explained because the industries in this segment are important suppliers of raw materials, especially to the furniture sector. Among the various existing markets that drive the forestry-based sector, the furniture market stands out, which today has a strong image worldwide due to its high level of technical and aesthetic quality. The industry is globally responsible for revenues in excess of U.S. $200 billion per year, and developed countries such as the United States, Italy, Germany, Canada, France, Spain and the United Kingdom figuring among the leading furniture producers (Garcia and Motta, 2006).

According to Leão and Naveiro (2009), 78.9% of the Brazilian furniture industry is represented by companies producing wood-based furniture, being subdivided into: office furniture, residential furniture, fitted cupboards or wardrobes, units for electronic devices and furniture components. Brazilian government incentives such as tax exemption on industrialized products have been beneficial to the furniture industries, which earned BRL 35.1 billion in 2011, 11.4% more than in 2010. Furthermore, public policies focused on the housing sector ("My Home My Life program") and the population's average income increase contributed to the high demand for furniture in the recent years.

The International Tropical Timber Organization – International Trade Center (ITC-ITTO, 2004) and Leão and Naveiro (2009) highlighted the growing use of MDP and MDF panels in furniture production. MDP is the reconstituted wood panel most produced and

[1] It was searched papers published between January 2003 and December 2013 in Journals indexed by the Web of Knowledge. The expressions searched in the articles' title and keywords were: LCA and wood-based products; LCA and wood panels; LCA and wood furniture.

Table 1
Prior LCA studies of wood-based products – wood panel sector.

Product	Nation	Reference
GLT	United States	Puettmann and Wilson (2004)
Hardboard	Austria	González-García et al. (2009)
Hardboard	Austria	González-García et al. (2011a)
LVL	United States	Wilson and Dancer (2004)
MDF	Spain	Rivela et al. (2007)
MDF	United States	Wilson (2010b)
MDF	Germany	Mitchell and Stevens (2009)
OSB	Luxembourg	Benetto et al. (2009)
OSB	United States	Earles et al. (2011)
OSB	United States	Kline (2005)
Particleboard	Spain	Rivela et al. (2006)
Particleboard	United States	Wilson (2010a)
Particleboard	Portugal	Garcia and Freire (2014)
Particleboard	Brazil	Silva et al. (2013a)
Plywood	Brazil	Teixeira et al. (2010)
Plywood	United States	Wilson and Sakimoto (2005)

consumed in the world, which may explain why this type of panel has received the most LCA studies (Table 1). The application of MDP is mainly for the manufacture of straight line furniture, such as tabletops, bedside cabinets, shelves and partitions (Biazus et al., 2010; Silva et al., 2013a; ITC-ITTO, 2004). Table 2 lists the main LCA studies of wooden furniture in the last ten years (2003–2013).

The LCA publications in Table 2 can be organized into residential furniture and commercial furniture, and the majority of these studies encompass case studies identifying hotspots and environmental improvement in manufacturing processes, including also cost savings, improved worker health and safety, decreased liability, and reduced regulatory burdens. Many suggestions for environmental improvements were developed based on ecodesign approaches, and focus on reductions of coating, gluing, cleaning, and wash-off materials, changes in manufacturing operations and the use of alternative wood furniture components.

There are more LCA studies on wood panels than on wooden furniture, and in the latter category, no LCA study for furniture manufactured in Brazil was found. This motivated the present article taking into account also the representativeness of the domestic market for wood-based furniture, and its growth prospects in the international field (Leão and Naveiro, 2009).

This paper analyzes sustainable strategies by assessing the environmental performance of a wardrobe made of MDP. The LCA technique was used in accordance with ISO 14040 and 14044 documents. After identifying the main environmental hotspots, some strategies for sustainable improvements were studied, and some scenarios were investigated in order to verify the environmental improvements resulting from changes in the product's life cycle.

The wardrobe life-cycle model and inventory are detailed in Section 2. The results are documented and discussed in Section 3. Section 4 shows some improvement opportunities that can be used to extend research in the area and integrate cleaner production into sustainability strategies. The conclusions are presented in Section 5 and may be extended to other lines of similar products that perform the same function and have similar characteristics.

2. Methodology

2.1. Case study

This article is characterized as a case study. The study took place in conjunction with a national company producing furniture, located in the State of São Paulo, Brazil, with its identity withheld for strategic reasons. The product evaluated was the wardrobe shown in Fig. 2 with dimensions 2670 mm × 606 mm × 2323 mm (width × height × depth). Subsequently, an arrangement of the product and a table summarizing a description of each of its components are shown in Fig. 3.

The wardrobe was selected for this study due to its representativeness in the domestic furniture market, leading with 13.7% of sales according to the Institute of Studies and Industrial Marketing (IEMI, 2012); and because it represents 40.0% of the company's total sales and requires 68.0% of all mass inputs consumed by the company.

Given that it is a LCA case study, the methodology of applying the technique was organized as follows: Definition of Goal and Scope, Analysis of the Life cycle inventory (LCI), Assessment of the Life-cycle impact (LCIA) and the Interpretation. The computational tool GaBi Software and Databases, Professional 4.4 version, was used for the life cycle modeling process.

2.2. Goal and scope definition

The first step defines the goal, which was to evaluate the life cycle of a wardrobe. The second step was to define the scope of the study. For ISO, 2006a,b, the scope stipulates items such as: the functional unit, reference flow, and the product system. For the wardrobe under study, the functional unit should represent qualitative and quantitative aspects of the storage of goods for personal use. With regard to the qualitative aspects, the wardrobe was used to store personal goods the home environment. The wardrobe total storage volume was 3.7 m^3, with a storage capacity of up to 40 kg. With regard to the implementation of the product function, the wardrobe has an average useful life of 5 years, which includes clothes storage, apparel and small personal items with no humidity. Thus, the functional unit of the study was: *40 kg of goods stored/5 years or 3.7 m^3 of goods stored/5 years*. The reference flow to comply with the functional unit was: *one wardrobe unit*.

The product system is detailed in Fig. 4, and it has three main stages, in a cradle-to-gate perspective, as follows: the raw materials supply, manufacturing and distribution of product.

2.2.1. Raw materials supply – primary component

The inventory data to produce MDP was extracted from Silva et al. (2013a), which evaluated the cradle-to-gate life cycle of MDP in Brazil. The MDP examined is a composite material, composed of wood particles and a synthetic adhesive based on urea-formaldehyde (UF) resin. The particleboard is the main integrating component of the wardrobe, which has the role of shaping

Table 2
Previous LCA studies of wood-based products – wood furniture sector.

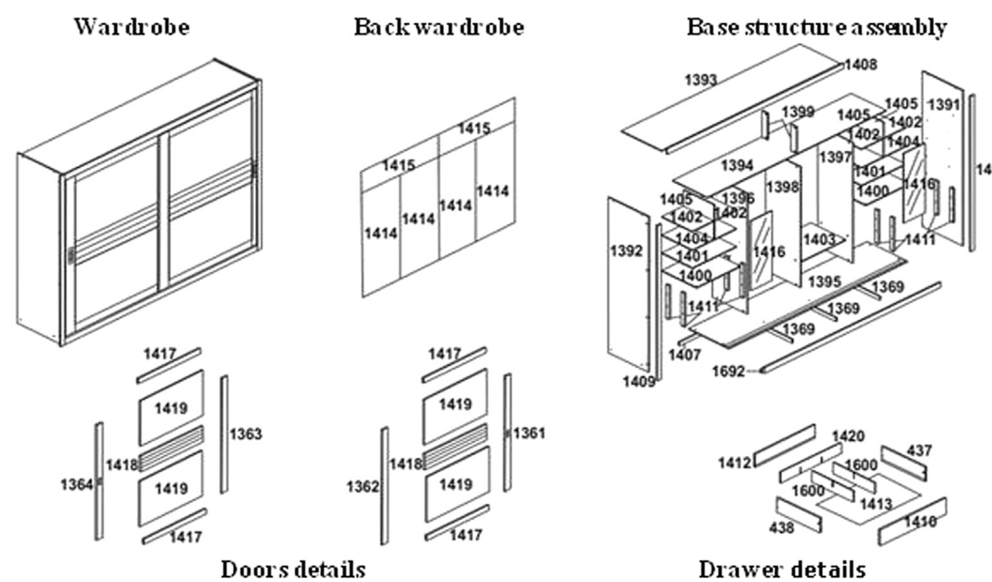
Product	Nation	Reference
Wood coatings, office chairs and conference/visitor chairs	Norway	Askam et al. (2012)
Childhood furniture (convertible cot into bed, study desk, and bedside table)	Spain	González-García et al. (2012)
Wood chairs	Norway	Skaar and Jorgensen (2012)
"Indoor products" (a convertible cot/bed, a kitchen cabinet, an office table, a living room furniture, a headboard, youth room accessories and a wine crate); "Outdoor products" (a ventilated wooden wall and a wooden playground)	Spain	González-García et al. (2011b)
Wood surface coatings and wood table	Sweden	Gustafsson and Börjesson (2007)
Office furniture (AirTouch table, Garland desk)	United States	Spitzley et al. (2006)
Wood based boards, surface and edge covering	Spain	Bovea and Vidal (2004)

Fig. 2. Object of study – wardrobe made from MDP.

and supporting the structure of the furniture design. Finally, the MDP produced is transported by a EURO 3 truck to the furniture industry, and the distance assumed was 200 km, as shown in Table 3.

2.2.2. Raw materials supply – secondary components

Other components used to manufacture the wardrobe were: polypropylene, steel, and paperboard, all of which, according to the stipulated proportions, represent around 5.0% of the total mass of inputs in the product system. Polypropylene is used to manufacture handles for the doors and cabinet drawers; steel components were applied to connect the furniture parts, such as hinges and screws; and paperboard is used in the assembly of boxes to pack the components of the furniture produced. Thus, for the production chain of polypropylene, steel and paperboard, the LCI data available in the GaBi software were adopted in the system boundaries.



Code	Item description	N° of pieces	Dimension (mm)	Code	Item description	N° of pieces	Dimension (mm)
1391	Right side	1	585x2320x15	1409	Side frame	2	55x2320x18
1392	Left side	1	585x2320x15	1410	Drawer front	6	150x585x15
1393	Upper base	1	585x2598x15	1411	Drawer spacer	8	58x505x25
1394	Luggage base	1	505x2598x15	437	Drawer right side	6	130x383x12
1395	Bottom base	1	585x2598x18	438	Drawer left side	6	130x383x12
1396	Inner left side	1	505x1802x15	1412	Oppositive back	6	120x539x12
1397	Inner right side	1	505x1802x15	1413	Drawerback	6	384x551x3
1398	Inner middle side	1	505x1802x15	1414	Back	4	653x1822x3
1399	Luggage door-	2	80x395x15	1415	Luggage locker back	2	412x1310x3
1400	Drawer cover	2	505x1802x15	1416	Door mirror	2	310x1037x12
1401	Shelf	2	445x628x15	1361	Right side for right	1	100x2190x25
1402	Upper shelf	4	440x311x15	1362	Left side for right door	1	100x2190x25
1403	Bottom shelf	1	505x638x15	1363	Right side for left door	1	100x2190x25
1404	Bored shelf	2	445x638x15	1364	Left side for left door	1	100x2190x25
1405	Split	2	445x515x15	1417	Larger traverse	4	100x1150x18
1369	Locking	3	55x2598x15	1418	Door Largest traverse	2	300x1150x18
1407	Back baseboard	1	55x2598x15	1419	Larger door panel	4	1170x860x6
1692	Baseboard	1	55x2558x15	1600	Lower split	4	100x373x6
1408	Frame	2	80x2558x18	1420	Larger split	2	100x539x6

Fig. 3. Scheme for assembling the wardrobe and its constituent elements.

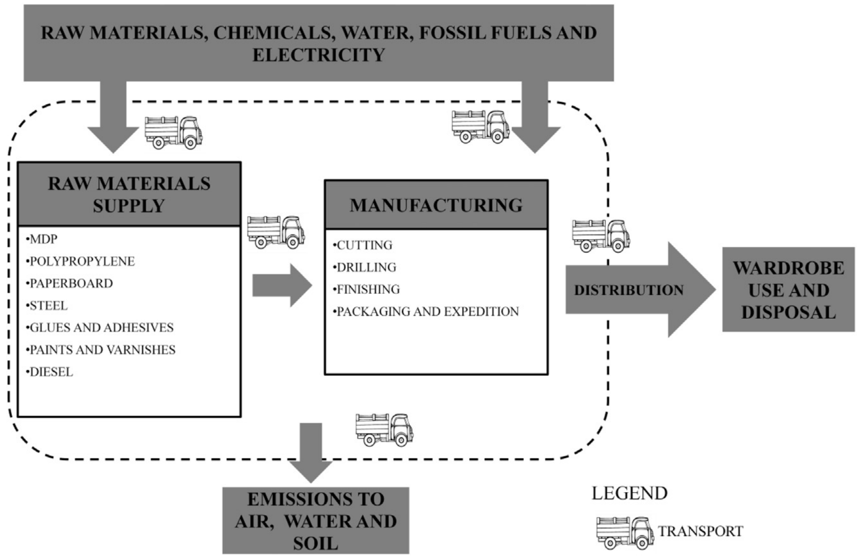


Fig. 4. Product system of the production of the wardrobe.

Furthermore, according to Fig. 4, the raw materials supply stage also includes the supply of synthetic adhesives and glues (hot melt), paints and varnishes for the industrial manufacture of the wardrobe, and diesel for the transportation process of inputs to the furniture industry. However, the inclusion of the supply chain of these resources was not taken into consideration within the boundaries of the product system, with the exception of the supply chain of diesel, which was taken from the GaBi database. All distances assumed for the transportation of these resources are listed in Table 3.

2.2.3. Manufacturing

All inventory data used were from primary source, collected directly at the furniture company studied. The consolidated LCI of the wardrobe manufacturing phase is presented in Section 2.3, Table 4. The wardrobe production process can be organized according to the activities as follows in Fig. 5: cutting, drilling, finishing, and packaging and expedition. Electricity input is the main resource consumed at the manufacture level. In this stage, the LCI data for the electricity generation (Brazilian mix) was taken from GaBi database.

2.2.4. Product distribution

Finally, regarding the product distribution different distances and shipping charges incurred for the functional unit are shown in Table 3. The different distances assumed are related to the product consumption in various regions in Brazil.

Table 3
Transport and distribution distances.

Description	Distance (km)	Total weight (t)	t * km
MDP	200	2.35E-01	46.94
Polypropylene parts	300	9.14E-03	2.74
Steel parts	300	1.57E-02	4.71
Glues and adhesives	200	7.27E-04	0.15
Paints and varnishes	250	4.86E-03	1.22
Paperboard	300	2.22E-02	6.67
Distribution (Southeast)	1200	2.26E-01	271.08
Distribution (Midwest/South)	1800	2.05E-02	36.96
Distribution (Northeast)	4000	7.07E-03	30.80
Distribution (North)	4600	2.57E-03	11.81

2.3. Life cycle inventory (LCI)

The attributional model was adopted for the wardrobe's LCI modeling (International Reference Life-cycle Data System – ILCD, 2010). Table 4 presents the LCI dataset for the wardrobe manufacture.

2.4. Life cycle impact assessment (LCIA)

Based on the selected impact categories and the EDIP-97 method (Wenzel et al., 1997), the environmental hotspots were measured as indicated in Table 5. The results are expressed in the most critical case of the product distribution stage – the distance of 4600 km (see Table 3).

The EDIP-97 is a midpoint method, and it was chosen because it is based on global models not developed specifically for European conditions, unlike more updated databases such as IMPACT 2002(+), EDIP 2003, and ReCiPe 2008. There is no Brazilian LCIA method available yet, which is why this premise was assumed for the LCIA phase.

2.5. Interpretation

The Interpretation phase may be organized in three stages: the identification of hotspots, the evaluation of hotspots and the conclusions and recommendations. The interpretation adopted followed the aim of this study, in Section 3, the hotspots were identified, in Section 4, the improvement opportunities based on

Table 4
Inventory of the wardrobe cradle-to-gate life cycle.

Inputs		Outputs	
Resources and materials		**Solid waste**	
Polypropylene parts	9.14 kg	MDP waste	29.90 kg
Steel parts	15.70 kg	Paints waste	0.74 kg
Paints and varnishes	4.82 kg	**Product**	
MDP	235.00 kg	Wardrobe	257.00 kg
Glues and adhesives	0.72 kg		
Paperboard	22.20 kg		
Energy			
Electric power	333.60 MJ		

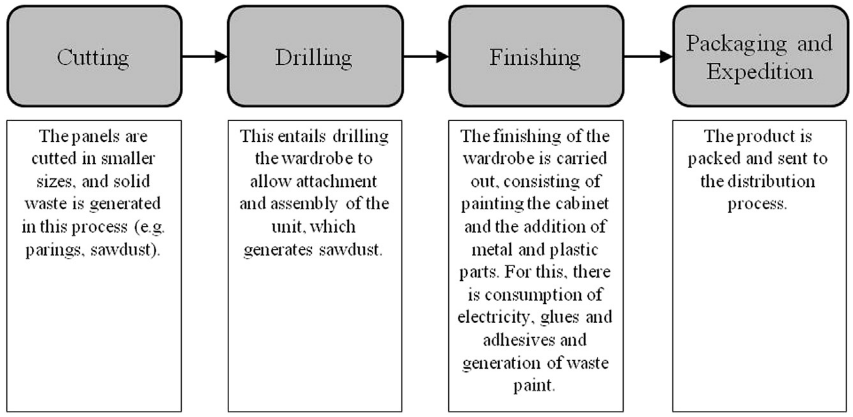


Fig. 5. Wardrobe manufacturing process.

some environmental sustainability strategies were defined, and the conclusions and recommendations were organized in Section 5.

3. Results of impact assessment

Table 5 summarizes the overall results of potential impacts for the product system.

Fig. 6 shows the environmental profile (6a) and the potential environmental impacts of the product system per life cycle stage (6b). It can be seen in Fig. 6b that the contributions from the raw materials supply stage ranged from 24.0% for HTS to 100.0% of impacts for CES; whereas the manufacturing stage of the wardrobe was responsible for 0.5% for HTA to 34% for OD; and the distribution stage contributed with 1.5% for HTA to 76% for HTS. It is then observed that the manufacturing stage offers the lowest contribution to the environmental impacts of the wardrobe. Moreover, the manufacturing stage accounted for less than 10% of total impacts for the wardrobe life cycle (see Fig. 6a).

3.1. Global warming (GW)

More than 50.0% of GW impacts were related to the stage of obtaining raw materials, mainly due to the impacts of the MDP used in the manufacturing of the wardrobe. The MDP was responsible for 43.0% of the GW impacts, mainly as result of the industrial production phase of the panel, due to the impacts of the supply chains of the UF resin and of the electricity. However, it is important to note that due to the forestry production phase of the MDP, there is a carbon sequestration from the atmosphere of 538.14 kg $CO_{2\text{-Eq.}}$ Subtracting from this value the 290.75 kg $CO_{2\text{-Eq.}}$ of fossil origin, it was found a carbon credit of − 247.39 $CO_{2\text{-Eq.}}$.

Table 5
Results of the potential impacts of the wardrobe cradle-to-gate life cycle.

Impact category	Reference unit	Impact value
Global warming (GW)	kg $CO_{2-\text{Eq.}}$	290.75
Ozone depletion (OD)	kg $R_{11-\text{Eq.}}$	4.3E-6
Photochemical oxidation (PO)	kg $C_2H_{4-\text{Eq.}}$	0.18
Acidification (AC)	kg $SO_{2-\text{Eq.}}$	1.49
Chronic ecotoxicity (Soil) (CES)	$m^3_{\text{-Eq.}}$	11,042
Acute ecotoxicity (Water) (AEW)	$m^3_{\text{-Eq.}}$	444.67
Chronic ecotoxicity (Water) (CEW)	$m^3_{\text{-Eq.}}$	4921.7
Human toxicity (Air) (HTA)	$m^3_{\text{-Eq.}}$	7.08E+08
Human toxicity (Water) (HTW)	$m^3_{\text{-Eq.}}$	306.16
Human toxicity (Soil) (HTS)	$m^3_{\text{-Eq.}}$	12.983
Nutrient enrichment (NE)	kg $NO^{-3}_{\text{Eq.}}$	1.64

3.2. Ozone depletion (OD)

For the OD category, 62.0% of the impacts occurred at the raw materials supply stage, namely: 40.0% of the impacts due to the paperboard and 22.0% due to the MDP life cycle − mainly related to the electricity consumption. Furthermore, 34.0% of the impacts were due to electricity consumption in the manufacturing stage of the wardrobe.

3.3. Photochemical oxidation (PO)

85.0% of the PO impacts occurred in the stage of raw materials supply, being 67.9% deriving from the MDP life cycle, due to the impacts during the industrial production of the panel, such as free formaldehyde air emissions arising from the use of UF resin.

3.4. Acidification (AC)

In this category, 75.0 to 60.0% of the impacts occurred during the raw materials supply stage and 18.0–30.0% during the product distribution stage, respectively, for transport distances of 1200–4600 km. Therefore, in this impact category the distribution stage was relevant depending on the distance considered. Most of the raw materials supply impacts were due to the diesel consumption in the transport operations, especially during the MDP life cycle, because of the field operations in the forest production phase, and due to the heavy fuel oil used as an energy source in the boilers during industrial MDP production.

3.5. Ecotoxicity (EC)

With regard to ecotoxicity the impacts were evaluated by compartment, as shown in Table 5. For CES, approximately 100.0% of the impacts were from the raw materials supply due to the emissions of free formaldehyde during the industrial production of the MDP. For AEW, from 85.8 to 64.3% of impacts were related to the raw materials supply due to the UF resin use during the MDP manufacturing process; from 11.2 to 35.7% of impacts were related to the product distribution stage, respectively, for the distances of 1200–4600 km, mainly due to the diesel consumption. For CEW, 67.0% of the impacts occurred predominantly in the raw materials supply, especially as result of free formaldehyde emissions during use of UF resin in the MDP production.

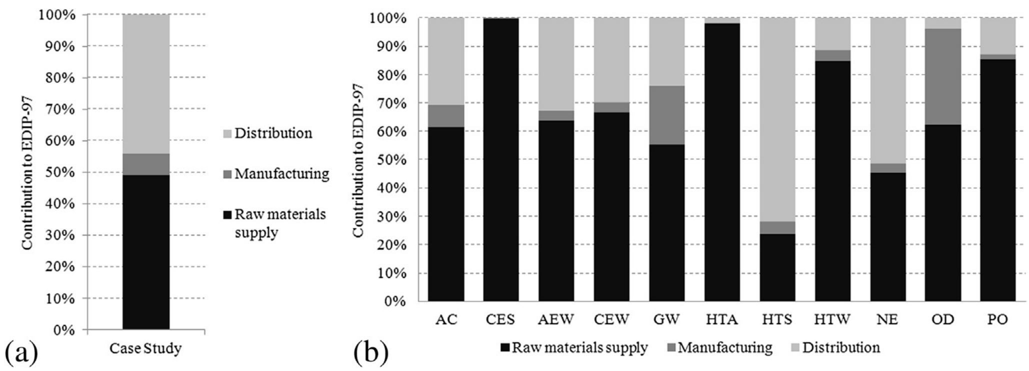


Fig. 6. Environmental profile (a) and potential impacts of the product system per life cycle stage (b).

3.6. Human toxicity (HT)

Considering the existing three compartments, 98.0% of the HTA impacts occurred at the stage of raw materials supply due to emissions of free formaldehyde during consumption of UF resin to produce the MDP. For HTW, 85.0% of the impacts were caused by the raw materials supply due to heavy metal emissions during the production of steel used in the manufacture of the connecting components used in the wardrobe. And for HTS category, from 55.0 to 22.0% of the impacts occurred in the raw materials supply stage because of free formaldehyde emissions from UF resin use, and from 45.0 to 72.0% of impacts were from the stage of the product distribution, respectively, for distances of 1200 and 4600 km, highlighting emissions of VOCs (volatile organic compounds) during use of diesel in transportation activities.

3.7. Nutrient enrichment (NE)

74.0–46.0% of the impacts were due to the raw materials supply and from 20.0 to 51.0% of the NE impacts due to product distribution stage, respectively, for the distances of 1200–4600 km. For this category again the product distribution stage proved to be relevant depending on the distance considered, as a result of diesel consumption in the transport operations. 50.0% of the raw materials supply impacts were due to the MDP, owing chiefly to the consumption of fertilizer sources of nitrogen–phosphorus–potassium (NPK) during the phase of forest production and due to the use of UF resin in the industrial production of the panel.

4. Cleaner production into sustainability strategies

This section presents a discussion of the possibilities for improving sustainability in the wardrobe life cycle, based on studies identified in the literature and analysis of alternative scenarios.

4.1. Strategies for improving sustainability in the wardrobe life cycle

Based on the interpretation of results in Section 3, the stages that present the greatest opportunities for environmental improvements were the raw materials supply, followed by the distribution stage, and the manufacturing stage.

With regards to the representation of each impact category for the overall environmental impacts of the product system, Fig. 7 shows the normalized impact results. In this case, the Normalization process was applied in accordance with the EDIP-97 method.

From Fig. 7, it is notable that the HTS, GW and AC impact categories totaled 68.0% of the overall wardrobe life cycle impacts. Considering these impact categories, in the following three bullet points are presented some general and possible sustainable strategies for environmental improvements in the wardrobe life cycle.

- *Human toxicity (soil)*: approximately 70.0% of the HTS potential impacts come from the distribution stage, in particular by emissions of VOCs. Thus the actions of environmental improvements consist of optimizing transport processes by reducing the volume occupied by the wardrobe and improving the environmental performance of the transport system used, either by replacement of the trucks or the fuels. For the case in question, it is recommended that partnerships be established between with transport companies for the replacement of the diesel used by other cleaner fuels. The search for new distribution routes for the product should also be undertaken, focusing on shorter distances;
- *Global warming:* the raw materials supply was the most important contributor to the GW category. The impacts identified were essentially related to the MDP cradle-to-gate life cycle. One suggestion would be to evaluate the partial or total replacement of this material by other ones, by conducting

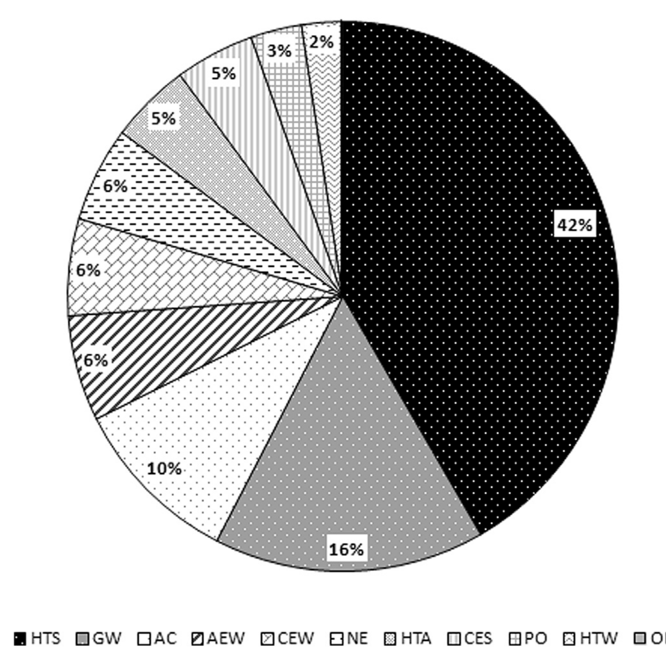


Fig. 7. Global environmental impacts of the wardrobe by impact category.

comparative LCAs, either through the use of similar panels such as MDF, or through the use of plastic and metal materials adopted in the furniture industry. The use of a mix of such alternative materials to produce the wardrobe could also be analyzed in details.

- *Acidification:* the stage of raw materials supply was highlighted in this category, followed by the distribution stage. For both, the AC impacts were primarily related to the consumption of fossil fuels such as diesel. Thus, the proposed improvement action consists of replacing the diesel by an alternative fuel with lower sulfur content in its composition.

From these results, it can be summarized the following sustainable strategies for the wardrobe life cycle production:

- To optimize the transport systems, i.e., to look for new routes and shorter transport distances, and the replacement of diesel fuel with other ones (e.g., the opening of new factories or the creation of synergies between the same sector industries, use of biodiesel or use of diesel with lower sulfur content);
- To replace partially or totally the MDP by addition of alternative materials during the furniture manufacture.

Based on the list of LCA studies of wooden furniture provided in Section 1 (see Table 2), in Table 6, we correlated these prior contributions with the two sustainable strategies selected in this study.

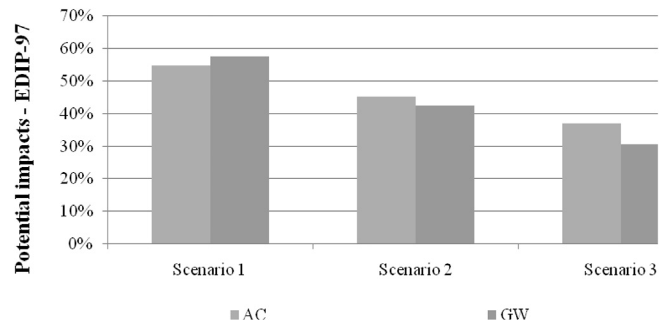


Fig. 8. Comparative analysis of the scenarios studied for categories AC and GW.

The main idea was to extract relevant contributions to subside a scenario analysis for each sustainable strategy defined.

Based on Table 6, five prior studies were found that directly contribute to the sustainable strategy of replacing the MDP by alternative materials, especially regarding to using recycled wood into the manufacturing panel process. On the other hand, no articles were found regarding the strategy of replacing diesel with other environmentally benign alternatives.

In this sense, the next section presents some alternative scenarios that were modeled into GaBi software aiming to quantify the possible reduction of environmental impacts arising from the

Table 6
Contributions of the past LCA studies of furniture products into the sustainable strategies selected.

Sustainable strategies selected	Reference	Product	Product system	LCIA method	Contributions to the field
To optimize the transport systems	No articles found	No articles found	No articles found	No articles found	No articles found
To replace the MDP by alternative materials	Bovea and Vidal (2004)	Wood based boards, surface and edge covering	Cradle-to-gate	Ecoindicator 99	▪ The use of recycled wood in the production process of wood based boards can reduce overall environmental impacts. ▪ Standard particleboard showed lower environmental impacts than the standard fibreboard investigated because the former had a 90.0% of recycled wood and the fibreboard only 10.0%.
	Spitzley et al. (2006)	Office furniture (AirTouch table, Garland desk)	Cradle-to-grave	TRACI	▪ Particleboard produced with wood wastes (e.g., from plywood industry) have no burdens associated with their use as a raw material; all impacts can be allocated to other timber products.
	González-García et al. (2011b)	Office table	Cradle-to-gate	CML 2	▪ The reuse (two uses) of boards in the production process was proposed. Reductions of total CO_2 equivalent emissions were highlighted.
	Askam et al. (2012)	Wood coatings, office chairs and conference/visitor chairs	Cradle-to-grave	Not defined	▪ Minimization of materials improves environmental performance during furniture production – higher recycled material content is beneficial.
	González-García et al. (2012)	Childhood furniture (convertible cot into bed, study desk, and bedside table)	Cradle-to-gate	CML 2	▪ Reuse of internal waste in manufacturing of panels can reduce environmental impacts mainly for OD, human toxicity and NE. ▪ Promoting the use of recycled plastic materials in some elements of furniture components can especially reduce PO and abiotic depletion impacts.

application of the sustainable strategy: *addition of alternative materials to replace MDP in the wardrobe life cycle*. It was studied the use of wood waste as an alternative raw material in substitution of virgin wood to produce the MDP – the consumption of virgin wood grown in the field is the current scenario that prevails in the panel industries in Brazil (Silva et al., 2013a).

4.2. Analysis of scenarios

Fig. 8 shows an analysis of scenarios concerning the influence of the addition of wood waste (parings, sawdust, chips) for the manufacture of MDP based only on the AC and GW categories, bearing in mind the large representation of the panel in these two categories. This scenario analysis also proved to be interesting because in European countries and the United States most of the panels are already produced even using up to 100% wood waste from other sawmills (Rivela et al., 2006, 2007; Santos et al., , 2014; Garcia and Freire, 2014; Silva et al., 2013a; Wilson, 2010a).

According to Silva et al. (2013a) to produce 1 m^3 of MDP requires the consumption of 687.3 kg of wood (1.45 m^3). Therefore, the scenario analysis considered substituting 687.3 kg of wood/m^3 of MDP by 50% (Scenario 2) and 100% (Scenario 3) of wood waste. It assumed transporting the wood waste by truck for a distance of 80 km between the source location and the panel factory, and that the wood waste would come from companies producing softwood lumber. As the LCI dataset for lumber production in Brazil was not found in the literature, the LCI data was taken from Milota et al. (2006), for the production of lumber in the United States.

Milota et al. (2006) used a mass allocation criterion for wood waste of 44% of all the impacts of sawn lumber production. In this case, adaptations to the inventory dataset were made, such as to substitute the distribution of electricity and the diesel fuel production to reflect the Brazilian context. The manufacturing stage of the wardrobe and the product distribution were not evaluated in this scenario, since it was considered that the potential impacts would not be changed by the proposed analysis.

Thus, from the assumptions set forth above the following scenarios were created:

- *Scenario 1:* current model, using 100% virgin wood (687.3 kg/m^3 MDP) without the addition of any alternative type of raw material;
- *Scenario 2:* use of 50% virgin wood (343.7 kg/m^3 MDP) and 50% of wood waste (343.7 kg/m^3 MDP);
- *Scenario 3:* 0% use of virgin wood and 100% wood waste (687.3 kg/m^3 MDP).

In Fig. 8 the potential impacts were determined and normalized using the EDIP-97 method. It is noted that there was a general reduction in potential impacts proportional to the insertion of wood waste in the production of the MDP.

Comparing scenarios 1 and 2, the potential impacts have been minimized by more than 20.0% for the evaluated categories. The largest reduction of impacts occurred for GW (27.0%), essentially due to lower demand for virgin wood in the forest plantation – highlighting the impacts associated with lower consumption of NPK fertilizers. The impacts for AC reduced by 20.0%, mainly by lower diesel consumption in field operations (i.e. use of tractors and trucks) in the cultivation of forest wood.

Comparing scenarios 1 and 3, there was a global minimization of potential impacts of more than 30.0%, because this scenario proposed the use of 100% of sawmill waste. Again, the greatest reduction of potential impacts occurred in the GW category (48.0% lower relative impacts) due to lower use of NPK fertilizer. For AC, the potential impacts were relatively 32.0% lower, again due to lower diesel consumption in field operations.

For the wooden wardrobe studied, it can be concluded that the use of wood waste as a raw material for the production of the MDP can present environmental advantages in that it reduces the demand for virgin wood cultivated for this purpose and, therefore, reduces the environmental impacts of the forest production phase for GW and AC.

However, in order for there to be environmental benefits as shown in Fig. 8, some variables should be studied case by case, as follows:

- The origin of the alternative raw material, inventorying all relevant environmental aspects of its life cycle generation;
- The amount of raw material to be used in the manufacture of panels;
- Allocation criteria to be considered for the raw material – an important issue when considering waste materials; and
- The distance to be covered along the route of the transportation.

It is important to point out that the four variables mentioned are the main ones to be dealt with when considering LCA studies in the production of wooden panels, using alternative raw materials in general. From this perspective, more studies on the issue are required. After all, as introduced in European countries and the United States, the use of waste such as those of wood in panel production is now a reality. Therefore, the analysis of such a change in the Brazilian context should also be studied, as well as the use of other waste materials that have technical and economic potential application in the manufacture of wood-based panels. As a positive consequence, a wooden panel with lower environmental impacts also generates products, such as furniture components of lower environmental impacts.

4.3. Other alternative options to promote cleaner production in the life cycle of the wardrobe

Besides evaluating addition of alternative raw materials to replace virgin wood (as in Section 4.2), other solution to improve the environmental profile of the wardrobe studied is to substitute the UF resin for alternative ones. According to results in Section 3, UF resin consumption during the MDP production was highlighted as an important hotspot responsible for impacts in almost all impact categories evaluated, mainly for GW, PO, EC, HT, and NE.

According to Silva et al. (2013a) and Santos et al. (2014), UF resin production is one of the main hotspots related to the overall environmental impacts of producing particleboards in Brazil. Moreover, González-García et al. (2012) explain that the environmental profile of final wood products – like furniture, can be significantly affected, especially due to human toxicity impacts caused by applying UF resin at the manufacture stage of wood-based panels.

With regards to the alternative options to promote cleaner production strategies, according to Wechsler et al. (2013), the manufacture of particleboards based on shells and castor oil resin can reduce formaldehyde emissions up to 5.0% compared to traditional particleboards made with UF resin. However, other available alternatives are: the use of UF resin with a lower formaldehyde content (Hosseini and Fadaei, 2013), and the substitution of UF resins for alternatives from renewable sources, while also considering other synthetic-based resins.

Renewable compounds based on lignin, cashew nutshell liquid (Kim, 2010), natural tannin (Kim, 2009), and castor oil (Varanda et al., 2013) have been successfully applied in recent years to produce a wide range of wood panels. However, these studies did not verify the global impacts of such alternative resins from a life cycle perspective. In 2011, González-García et al. (2011a,b) analyzed the environmental impacts with the introduction of a laccase system in the hardboard production by substituting phenol-formaldehyde resin with a two-component adhesive with a wood-based phenolic material and a laccase activated lignin. The results showed that the laccase system had relatively small effects on the AC and NE categories.

Regarding synthetic-based resins, for the UF resin manufactured in Brazil, Silva et al. (2013b) verified that the toxicological impacts (ecotoxicity and human toxicity impacts) were higher than 30.0% in comparison to the non-toxicological impacts studied; they also suggested further research in order to compare UF resins with other ones, for instance, the melamine-urea-formaldehyde (MUF) resin. Thus, more recently, Silva et al. (2015) provided an LCA study comparing the application of MUF and UF resins to produce MDP, showing that MUF can replace UF resin mainly due to its lower contributions to PO, EC and HT.

Finally, more LCA studies are needed to scientifically document the environmental profile of using such alternative resins to potentially substitute UF resin, as few studies have been conducted.

5. Conclusions

This paper showed an LCA case study of furniture in Brazil for the production of a wardrobe model. It was highlighted and investigated in details the most relevant categories of impact – human toxicity, global warming and acidification – and the stages that most contributed to these impacts – raw material supply and product distribution. It was possible to confirm that the greatest gains from the environmental point of view are beyond the physical limitations of the company, since the manufacturing process was responsible for only 7% of the global environmental impacts of the wardrobe life cycle.

The main contribution of this research was to fill the gap of LCA studies of wood-based products in Brazil. The furniture sector has a significant participation in the Brazilian economy and the study of environmental performance of such products has been not adequately addressed. Moreover, this paper reviewed the most relevant wood-based furniture LCA studies in literature to establish more sustainable strategies to be applied by the furniture industry studied.

Two sustainable strategies for improving the wardrobe environmental performance were presented: to optimize the transport systems and to partially or totally replace the MDP by alternative materials. New routes and short transport distances combined with the replacement of diesel fuel could reduce the hotspots and should be thoroughly investigated. With regards to the MDP replacement, a comparative scenario analysis showed that the use of wood waste as raw material to produce particleboard can provide an environmentally benign alternative.

However, this study has some limitations. The first relates to the scope of the product system, which did not consider the product's use and end-of-life phases. Thus, depending on how the product is discarded, there may be changes in the environmental profile of the product life cycle. Thus, to realize a complete cradle-to-grave LCA of the product studied is essential to identify the most appropriate sustainable strategies. The second is associated with secondary data sources used in the LCI phase, which mostly represent the reality of other countries (i.e. supply chain of steel, polypropylene and paperboard components). It is believed that with the development of databases for Brazil this limitation can be overcome and the results may reflect greater accuracy. On the other hand, it is important to note that steel, polypropylene and paperboard components amounted only 5.0% of the total inputs inventoried.

There are several opportunities for future work: it is necessary to broaden the scope of the wardrobe life cycle, including the stages of use and end-of-life; to evaluate other sustainable strategies, such as use of renewable energy sources (e.g., to substitute diesel fuel); to investigate the use of alternative and biodegradable raw materials to substitute virgin wood and UF resin during panel manufacturing and the possible technical changes required in the manufacture process of panels; and finally, the inclusion of economic and social aspects in the life cycle assessment of the wardrobe studied.

Acknowledgements

The authors are grateful for the financial support provided by CNPq (The National Council for Scientific and Technological Development) for grants 135162/2010-6 and 152754/2010-5; and by FAPESP (The São Paulo Research Foundation) for the grants 2011/03816-6 and 2013/06736-9. Also, the authors are grateful for the comments and suggestions made by reviewers, which improved the quality of the paper.

References

ABIPA, Brazilian Association of the Wood Panels Industry, 2014. Key Figures. Available at: http://www.abipa.org.br/numeros.php (accessed 17.03.14.).
ABRAF, 2013. Brazilian Association of Forest Plantation Producers – Yearbook Statistical ABRAF: Base Year 2012. STCP Engenharia de Projetos, Brasília.
Askam, C., Hanssen, O.J., Gade, A.L., Nereng, G., Aaser, C.P., Christensen, P., 2012. Strategy tool trial for office furniture. Int. J. Life Cycle Assess. 17, 666–677.
Benetto, E., Becker, M., Welfring, J., 2009. Life-cycle assessment of oriented strand boards (OSB): from process innovation to ecodesign. Environ. Sci. Technol. 43 (15), 6003–6009.
Biazus, A., Hora, A.B., Leite, B.G.P., 2010. Panorama de mercado: painéis de madeira, vol. 32. BNDES setorial, Rio de Janeiro, pp. 49–90.
Bovea, M.D., Vidal, R., 2004. Materials selection for sustainable product design: a case study of wood based furniture eco-design. Mater. Des. 25 (2), 111–116.
Chen, C.-C., Shih, H.-S., Shyur, H.-J., Wu, K.-S., 2012. A business strategy selection of green supply chain management via an analytic network process. Comput. Math. Appl. 64 (8), 2544–2557.
Earles, J.M., Halog, A., Shaler, S., 2011. Improving the environmental profile of wood panels via co-production of ethanol and acetic acid. Environ. Sci. Technol. 45 (22), 9743–9749.
Garcia, R., Motta, F.G., 2006. Mercado de móveis movimenta US$ 200 bilhões por ano. Rev. Madeira 97, 4–12.
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.
González-García, S., Feijoo, G., Widsten, P., Kandelbauer, A., Zikulnig-Rusch, E., Moreira, M.T., 2009. Environmental performance assessment of hardboard manufacture. Int. J. Life Cycle Assess. 14, 456–466.
González-García, S., Feijoo, G., Heathcote, C., Kandelbauer, A., Moreira, M.T., 2011a. Environmental assessment of green hardboard production coupled with a laccase activated system. J. Clean. Prod. 19 (5), 445–453.
González-García, S., Gasol, C.M., Lozano, R.G., Moreira, T.M., Gabarrell, X., i Pons, J.R., Feijoo, G., 2011b. Assessing the global warming potential of wooden products from the furniture sector to improve their ecodesign. Sci. Total Environ. 410-411, 16–25.
González-García, S., Lozano, R.G., Moreira, T.M., Gabarrell, X., i Pons, J.R., Feijoo, G., Murphy, R., 2012. Eco-innovation of a wooden childhood furniture set: an example of environmental solutions in the wood sector. Sci. Total Environ. 426, 318–326.
Gustafsson, L.M., Börjesson, P., 2007. Life-cycle assessment in green chemistry. Int. J. Life Cycle Assess. 12, 151–159.
Hosseini, S.M., Fadaei, M., 2013. Properties of particleboard made from UF with low-formaldehyde (E1). Int. J. Eng. 26 (1), 45–49.
IEMI, Institute of Studies and Industrial Marketing, 2012. Relarótio setorial 2012 – Polo moveleiro do Rio Grande do Sul, pp. 1–94 [in portuguese].
ILCD, International Reference Life-cycle Data System, 2010. ILCD Handbook. European Commission – Joint Research Centre – Institute for Environmental and Sustainability, Luxemburgo.
International Organization of Standardization, 2006a. ISO 14040: Environmental Management – Life-cycle Assessment-Principles and Framework. Geneva.
International Organization of Standardization, 2006b. ISO 14044: Environmental Management – Life-cycle Assessment-Requirements and Guidelines. Geneva.

ITC-ITTO, International Tropical Timber Organization – International Trade Center, International Wooden Furniture Markets, 2004. http://www.fao.org/forestry/23523-0f14bba18f78fa30aed5fcceaa0f41f69.pdf (accessed 30.08.13.).

Kim, S., 2009. Environment-friendly adhesives for surface bonding of wood-based flooring using natural tannin to reduce formaldehyde and TVOC emission. Bioresour. Technol. 100, 744–748.

Kim, S., 2010. The reduction of formaldehyde and VOCs emission from wood-based flooring by green adhesive using cashew nutshell liquid (CNSL). J. Hazard Mater. 182, 919–922.

Kline, E.D., 2005. Gate-to-gate life inventory of oriented strand board. Wood Fiber Sci. 37, 74–84 (CORRIM Special Issue).

Leão, M.S., Naveiro, R.M., 2009. Fatores de competitividade da indústria de móveis de madeira no Brasil. Rev. Madeira 119, 4–11.

Milota, M., West, C., Hartley, I., 2006. Gate-to-gate life cycle inventory of softwood lumber production. Wood Fiber Sci. 37, 47–57.

Mitchell, A., Stevens, G., 2009. Life-cycle Assessment of Closed Loop MDF Recycling: Micro Release Trial – Final Report [S.l.:s.n.].

Puettmann, M.E., et al., 2010. Cradle-to-gate life-cycle inventory of US wood products production: CORRIM phase I and phase II products. Wood Fiber Sci. 42, 15–28 (CORRIM Special Issue).

Puettmann, M.E., Wilson, J.B., 2004. Glued Laminated Beams-Pacific Northwest and Southeast. Phase I final report. Consortium for Research on Renewable Industrial Materials. CORRIM, Inc. Seattle: University of Washington.

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.

Rivela, B., Moreira, M.T., Feijoo, G., 2007. Life-cycle inventory of medium density fiberboard. Int. J. Life Cycle Assess. 12, 143–150.

Santos, M.F.N., Battistelle, R.A.R., Bezerra, B.S., Varum, H.S.A., 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.

Schweinle, J., 2007. Wood & other renewable resources: a challenge for LCA. Int. J. Life Cycle Assess. 3, 141–142.

Silva, D.A.L., Rocco Lahr, F.A., Garcia, R.P., Freire, F.M.C.S., Ometto, A.R., 2013a. Life-cycle assessment of medium density particleboard (MDP) produced in Brazil. Int. J. Life Cycle Assess. 18, 1404–1411.

Silva, D.A.L., Mendes, N.C., Varanda, L.D., Ometto, A.R., Rocco Lahr, F.A., 2013b. Life cycle assessment of urea formaldehyde resin: comparison by CML (2001), EDIP (1997) and USEtox (2008) methods for toxicological impact categories. In: Andrew, Y. C. Nee, Bin, Song, Soh-Khim, Ong (Eds.), Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP. Springer, Singapore, pp. 529–534.

Silva, D.A.L., Rocco Lahr, F.A., Varanda, L.D., Christoforo, A.L., Ometto, A.R., 2015. Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil. J. Clean. Prod. 96, 299–307.

Skaar, C., Jorgensen, R.B., 2012. Integrating human health impact from indoor emissions into an LCA: a case study evaluating the significance of the use stage. Int. J. Life Cycle Assess. 12, 151–159.

Spitzley, D.V., Dietz, B.A., Keoleian, G.A., 2006. Life-cycle Assessment of Office Furniture Products Life-cycle Assessment of Office Furniture Products. University of Michigan [s.n.].

Teixeira, C.E., Sartori, L., Finotti, A.R., 2010. Comparative environmental performance of semi-trailer load boxes for grain transport made of different materials. Int. J. Life Cycle Assess. 15, 212–220.

Thoemen, H., Irle, M., Sernek, M., 2010. Wood-based Panels – an Introduction for Specialists. Brunel University Press, London.

Varanda, L.D., Nascimento, M.F., Christoforo, A.L., Silva, D.A.L., Rocco Lahr, F.A., 2013. Oat hulls as addition to high density panels production. Mat. Res. 16, 1355–1361.

Wechsler, A., Zaharia, M., Crosky, A., Jones, H., Ramirez, M., Ballerini, A., Nuñez, M., Sahajwalla, V., 2013. Macadamia (Macadamia intergrifolia) shell and castor (Ricinos communis) oil based sustainable particleboard: a comparison of its properties with conventional wood based particleboard. Mater. Des. 50, 117–123.

Wenzel, H., Hauschilld, M.Z., Alting, A., 1997. Environmental Assessment of Products. Methodology, Tools and Case Studies in Product Development. Kluwer Academic, Dordrecht v.1.

Wilson, J.B., 2010a. Life-cycle inventory of particleboard in terms of resources, emissions, energy, and carbon. Wood Fiber Sci. 42, 90–106 (CORRIM Special Issue).

Wilson, J.B., 2010b. Life-cycle inventory of medium density fiberboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci. 42, 107–124 (CORRIM Special Issue).

Wilson, J.B., Dancer, E.R., 2004. Laminated Veneer Lumber – Pacific Northwest and Southeast. Phase II final report. Consortium for Research on Renewable Industrial Materials. CORRIM, Inc. Seattle: University of Washington.

Wilson, J.B., Sakimoto, E.T., 2005. Gate-to-gate life-cycle inventory of softwood plywood production. Wood Fiber Sci. 37, 58–73 (CORRIM Special Issue).