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Life cycle assessment in the furniture industry: the case study of an office cabinet

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Abstract

Purpose In an effort to reduce the environmental impacts of the furniture sector, this study aimed to diagnose the environmental performance of an office cabinet throughout its life cycle.

Methods An attributional life cycle assessment (LCA) was used, based on the *ISO 14044 Standard and ILCD Handbook*. The scope of the study considered the entire supply chain, from cradle to grave, including the steps of pre-manufacturing, manufacturing, use, and post-use of the product. The impact assessment method was the International Reference Life Cycle Data System (ILCD) 2011 midpoint.

Results and discussion The results identified that the most significant environmental impact of the furniture life cycle was due to the distances covered and production of the main raw material, wood medium-density particleboard (MDP).

The evaluation of transport scenarios showed environmental tradeoffs for truck fuel switches and environmental gains for the distribution of MDP from closer suppliers by truck, as well as from current supplier by truck and ship in the major categories. Furthermore, evaluation of the office cabinet post-use options showed that reuse, recycling, or energy recovery from waste cause significant environmental gains in the major categories. Wooden furniture is a potential carbon sink if its life cycle does not emit more greenhouse gases than its materials can store. The impacts of substitution scenarios varied depending on the type of product avoided.

Conclusions The LCA proved a powerful method to diagnose and manage environmental impacts in complex product systems. The sensitivity analysis showed that it is possible to reduce the environmental impacts and, at the same time, make the furniture industry increase its economic gains and net carbon stock in the anthroposphere.

Keywords Biogenic carbon · End-of-life · Life cycle assessment (LCA) · Office furniture · Sensitivity analysis · Transport distance

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1 Introduction

The furniture industry is one of the oldest sectors of the economy and involves the production of durable consumer goods used for storage, hanging, supporting, lying, sitting, working, and eating (Cordella and Hidalgo 2016). Particleboard is a panel manufactured from lignocellulosic materials, such as wood, with an organic binder (Food and Agriculture Organization (FAO) 2016), which started to be commercialised in the 1950s (Kouchaki-Penchah et al. 2016). The Brazilian wood panel (WP) and laminate flooring sectors occupied the 8th place in the 2015 world ranking

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(Brazilian Tree Industry (IBÁ) 2016). The WP demand growth in Brazil in the last few years occurred due to the replacement of sawn-wood and plywood, which are more expensive than WP and have supply limitations (Vidal and Hora 2014). Globally, wood waste is used in the production of WP, but in Brazil, the wood comes from planted forests (Vidal and Hora 2014). According to Centre for Industrial Studies (CSIL) (2015), office furniture accounts for 11% of total world furniture consumption. The office furniture market is worth US$47 billion, with the USA, China, Japan, Germany, and Brazil composing the largest share. Most Brazilian furniture factories are structured in semi-industrial production routes (Rapôso et al. 2012), accounting for 17,000 furniture facilities against 12 WP companies (Vidal and Hora 2014).

European legislative bodies are promoting resource-efficient and low-carbon economies in many sectors as the main strategy for generating wealth and jobs (European Commission (EC) 2011). Klein et al. (2015) investigated the latest studies in the forestry sector and found that wooden products are widely declared as "carbon neutral," although the life cycle literature shows that absolute carbon neutrality claims are incorrect. Rapôso et al. (2012) also argue that the furniture industry has limitations related to its process efficiency and reduction of material use, consequently the sector requires technological and managerial innovations. The furniture companies need to tailor their products to meet legal environmental requirements, as the consumers are motivated for environmental labelling initiatives, such as the Brazilian Technical Standards Association for Environmental Quality Label (Qualidade-ABNT-Ambiental). These actions indicate the increased demand for transparency of product environmental issues throughout the life cycle.

Life cycle assessment (LCA) provides support indicators that help identify opportunities to eliminate or minimise the environmental impacts of supply chains, within an impact category or a region, rather than by changing the type of impact or transferring it to another step (Sonnemann and Valdivia 2014). According to the ISO 14040 (2006) standard, ratified by Hou et al. (2015), LCA evaluates and interprets the interrelationships that occur between product and environment, as a quantitative method of environmental impacts that covers the whole life cycle of the product. Manzini and Vezzoli (2005) add that LCA is an inter-related strategy to Design for Environment (DfE), which is aimed at improving the environmental performance of products, services, and processes in any productive segment in which they are located.

Furniture gains attention in LCA of a net-zero-energy building, as it was responsible for 10% of the building's impact on global warming and non-renewable energy demand, and therefore it shall be considered in building's design (Hoxha and Jusselme 2017). In the furniture sector, recent studies focus on LCA and scenario evaluation through

sensitivity analysis in order to propose an ecodesign for products (González-García et al. 2011, 2012a, b; Iritani et al. 2015; Höglmeier et al. 2015). Furthermore, combinations of methods, such as service design principles and LCA, support sustainable development of product service systems (PSS) in the furniture design and manufacturing (Costa et al. 2015).

Chaves (2007) used LCA to develop design tools and strategies of environmental sustainability for the furniture industry, in order to guide designers to achieve effective results. Höglmeier et al. (2015) proposed the application of resource cascading, using the same resource unit in multiple successional applications as a viable means to improve the resource efficiency and decrease environmental impacts of wood-based products. The environmental issues of the Brazilian furniture sector gained attention through Silva et al. (2013), who evaluated the life cycle of wood medium-density particleboard (MDP) production and Silva et al. (2014), who evaluated an alternative particleboard made with sugarcane bagasse (PSB), both covering from cradle to gate. The latter found that PSB could replace the traditional MDP with better environmental performance. Santos et al. (2014) assessed PSB (*Saccharum* sp.) and particleboard from pine wood shavings (*Pinus elliottii*) in Brazil, and the results indicated that pine particleboard presented higher potential environmental impacts because the distance raw material was transported to the production site. Murphy et al. (2015) assessed the greenhouse gases (GHG) of several timber products (sawn-wood, wood chip, wood panel, and wood pellets) in Ireland and identified the largest contributions to overall emissions that came from forestry operations and transportation. Piekarski et al. (2017) evaluated the life cycle of wood medium-density fibreboard (MDF) from cradle to gate in Brazil and identified the main hotspots to be from natural gas consumption, urea-formaldehyde resin, electricity, and wood chip production and transportation to the plant.

Iritani et al. (2015) published the first furniture LCA study for Brazil. They confirmed that the greatest opportunities to minimise environmental impacts of furniture products are beyond the manufacturing step. The studied product was a wardrobe with extension from cradle to gate, and they identified the most significant environmental impacts in the stages of raw material supply and product distribution. They suggested two strategies to improve the environmental footprint of the product: improving the transport system and using alternative materials to manufacture MDP.

González-García et al. (2011) assessed the GHG emissions of wooden indoor and outdoor furniture in Spain from cradle to gate. They concluded that the production of inputs, such as wood-based materials, metals, energy, and transport of inputs to the manufacturing plant is the most important environmental issues. They proposed short-term improvements to reduce GHG up to 60%, which were also reflected in other categories. On the other hand, they claimed difficulties to achieve

considerable GHG reductions with long-term improvements for most of the studied products.

González-García et al. (2012a) conducted a LCA and DfE study to produce a wooden modular playground from cradle to gate. They found the manufacturing step to be the largest contributor to the environmental profile, which was 60% higher than all other categories, due to upstream processes such as wood-based material production and transport, as well as steel production. González-García et al. (2012b) conducted another LCA and DfE study to produce a children's furniture set made up of three different integrated units (bed, study desk, and bedside table) from cradle to gate. They encountered two pre-manufacturing processes that were considered environmental hotspots: production of electricity and wooden materials.

Linkosalmi et al. (2016) assessed the GHG emissions, counting both fossil and biogenic gases, of eight different types of furniture from cradle to gate and identified that transport of wooden materials did not contribute much as most distances were small (3 to 449 km). They argued that emissions are material specific and that the selection of materials and energy suppliers are key to reduce GHGs, including the biogenic carbon stored in wood-based materials.

Suter et al. (2016) identified that environmental benefits are achieved when wood-based materials replace conventional heat production and energy intensive materials, mainly at the end-of-life treatment of wooden products. However, none of the abovementioned furniture LCA studies assessed the environmental impacts of the post-use step (González-García et al. 2011, 2012a, b; Iritani et al. 2015; Linkosalmi et al. 2016). Van der Harst et al. (2015) verified that the model choice to include recycling in LCA influences the environmental impacts considerably and can stimulate recyclability of product materials. In this sense, this study aimed to model the supply chain of an office cabinet in Brazil to evaluate the environmental impacts along the life cycle and identify opportunities to reduce the impacts.

2 Methods and resources

This section describes the attributional LCA phases, based on ISO 14040 (2006), ISO 14044 (2006), and International Reference Life Cycle Data System (ILCD 2010).

2.1 Goal and scope

The product is an office cabinet with a sliding door, 900 mm width, 480 mm depth, and 1600 mm height (Fig. 1).

The manufacturing and transport data were collected for the year 2013 in a medium-sized Brazilian company located in the state of Bahia (BA) in the northeast of the country that is
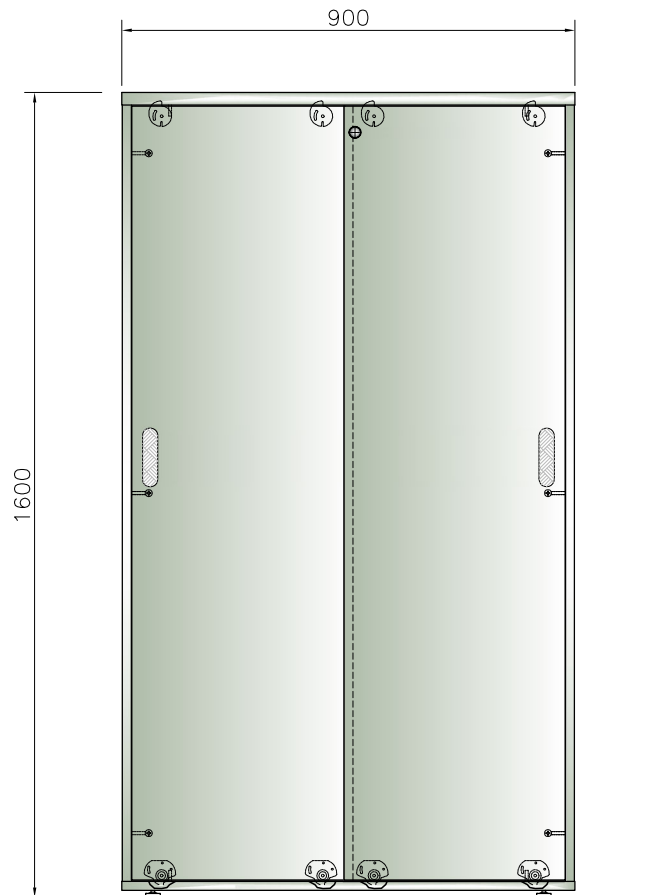

Fig. 1 The front view illustration of the office cabinet. Dimensions are given in millimeters (mm)

representative for the furniture sector. The manufacturing plant produces serial office furniture with modern machinery.

2.2 Product system

This LCA study covers cradle to grave, including the pre-manufacturing (production of inputs), manufacturing, use, and post-use (waste management) steps. The model used primary data in foreground processes (i.e., transport distances and manufacturing) and secondary data in background processes (materials, energy, transport, waste treatment) (Fig. 2).

The manufacturing step used MDP (25 mm thickness at 15.9 kg/m^2 and 18 mm thickness at 11.95 kg/m^2) in the office cabinet production batch. All material that arrives at the manufacturing plant is stored in a warehouse. The manufacturing process uses a specific software, *CORTE CERTO*, to optimise the cutting plan of wood boards of a given production batch, which minimises the amount of waste. The boards are cut and taped with polyvinyl chloride (PVC) tape. Then, the taped boards are machined and sent for
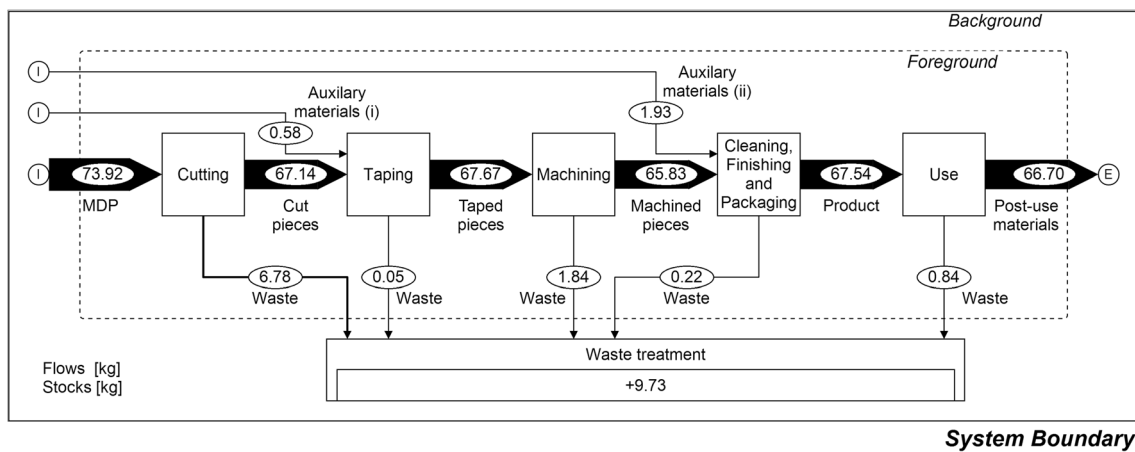
Fig. 2 Product system from cradle to grave. Import (*I*) states for the upstream datasets and export (*E*) states for downstream ones. *i* Auxiliary materials include PVC tape, glue, and soap; *ii* auxiliary

materials include cotton towel, solvent, paperboard, and plastic packages. Source: STAN 2 software (Cencic and Rechberger 2008)

cleaning. Afterwards, the furniture is assembled, the accessories are added, and the product is packed up.

Quantitative data of materials and energy consumed together with the losses generated at each stage of the furniture manufacturing were inventoried based on operator consulting, yield estimates, material weighing, machinery specification, cutting plan software, and balance sheets. The infrastructure of the manufacturing plant was considered negligible along with the cleaning and maintenance of the use step and were disregarded. The cut-off criteria used for mass lower than 1% included the infrastructure of manufacturing plant and packages of inputs. In this study, allocation by partitioning was not necessary as there was only one main product.

2.3 Life cycle inventory

The office cabinet life cycle encompasses four steps: premanufacturing, manufacturing, use, and post-use.

2.3.1 Pre-manufacturing

The production of material and energy inputs, as well as waste treatment, was obtained from the ecoinvent database. The uncoated MDP is produced from *Eucalyptus* sp., average density of 630 kg/m³, 8% moisture content, and representative for Brazilian market (Silva et al. 2013). For transportation, we listed the location of the suppliers of each component and calculated the respective distances to the manufacturing plant (Table 1).

The transport demand was calculated by multiplying the mass of each component by the respective distance (Table 1), multiplied by two to take into account the round trip.

2.3.2 Manufacturing

The manufacturing step accounts for the demand of inputs and waste treatment in the office cabinet production (Table 2). The

background datasets are presented in Table A1 of the Electronic supplementary material (ESM) 1. The electricity consumption in the stages of manufacturing was calculated based on the running time and energy demand of each machine. For 19 office cabinet units produced, the cutting stage spent 2 h in a *Giben Smart SE 90* of 24 kW, the taping spent 5 h in a *Giben Alfa 460* of 19 kW, and the machining spent 5 h in the *Weeke Homag Venture 06S* of 24 kW.

In the cutting stage, the mass of the MDP used to make an office cabinet was calculated based on data provided by *CORTE CERTO* software. After cutting the MDP, some pieces are taped (tape masses, 25 mm thickness at 0.04 kg/m and 18 mm thickness at 0.033 kg/m). We measured the side length of the board pieces to be taped. The tape mass was measured by an electronic scale.

Table 1 Transportation distances for each office cabinet component

Input	Address (city-state)	Distance (km)
Electricity	Lauro de Freitas-BA	0
MDP	Agudos-SP	2100
Hotmelt glue	Novo Hamburgo-RS	3160
PVC tape	Vargem Grande Paulista-SP	2065
Metal pieces	Caieiras-SP	1990
Furniture levelling foot	Caieiras-SP	1990
Metal pieces	Xaxin-PR	2430
Drawer slides	Xaxin-PR	2430
Screws	Joinville-SC	2530
Fasteners	Campo Grande-MS	2500
Cleaning products	Içara-SC	2930
Towel	Santa Mônica-BA	31
Profiles and angles	Simões Filho-BA	22
Paperboard package	Santo Amaro-BA	80
Plastic package	Ibirite-MG	1380

In the machining stage, the pieces are cut and pierced in different ways. The health impacts on the labourers from particulate matter are low as the machines have a dust exhaust system and the employees use personal protective equipment (PPE). It is assumed that all particulate matter end up as solid waste. Afterwards, a towel and *RAZ* ® water solvent are used to clean the office cabinet pieces before assembly. The office cabinet assembly stage is manual and uses tools like screwdriver and hammer. Then, the end product is packed and stored.

The optimisation of the office cabinet manufacturing occurs with the use of MDP leftovers from the cutting stage to manufacture other products; hence, a cut-off rule was applied. The PVC waste from the tape edge and residual glue are sent to the local sanitary landfill. Cotton towel wastes from cleaning are also sent to the local landfill. The distance from the manufacturing plant to the local landfill is 10.5 km. The figures related to amount of waste are presented in Table 2.

2.3.3 Use

The use step includes only an estimation of the transportation of the furniture from the manufacturing plant to the consumer's home, totalling 50 km for the round trip, and the packaging waste. The maintenance and cleaning of the office cabinet were not included in the use step as we consider it a consumer decision. Cordella and Hidalgo (2016) noticed that the use step appeared to be negligible in furniture LCA and is not always taken into account.

2.3.4 Post-use

The post-use step accounts for the municipal waste collection and treatment at an incineration plant. The waste treatment processes were obtained from the ecoinvent database (ESM 1 (Table A2)). The distance between the user and the waste treatment plant was 10.5 km, multiplied by 2 to account for the round trip.

### 2.4 Software, database, and impact method

We used Simapro® 8 software to calculate the environmental impact results. The background data were obtained from the ecoinvent database with cut-off allocation (Wernet et al. 2016) version 3.3 (Moreno-Ruiz et al. 2016). Brazilian datasets were preferred, in the case of electricity and MDP, otherwise global or rest of the world datasets were chosen. The impact assessment method was the European International Reference Life Cycle Data System (ILCD) 2011 Midpoint version 1.09 (European Commission (EC) 2012) recommended

for ecolabel of wooden furniture (European Commission (EC) 2013), due to absence of a Brazilian one. The ILCD 2011 methods package evaluates the midpoint impacts of global warming (GW), ozone depletion (OD), human toxicity non-cancer effects (HT-n), human

Table 2 Inventory of the manufacturing step for an office cabinet

Manufacturing stages	Quantity	Unit	Comments
Cutting			
Input			
MDP	7.39E+1	kg	Measured
Electricity	2.53E+0	kWh	Calculated
Truck	3.10E+5	kg/km	Calculated
Output			
Cut pieces	1.00E+0	Set	
Leftovers	4.14E+0	kg	Calculated
Sawdust	2.64E+0	kg	Estimated
Particulates <2.5 μm, air	6.78E−2	kg	Estimated
Taping			
Input			
Cut pieces	1.00E+0	Set	
Electricity	5.00E+0	kWh	Calculated
PVC tape	5.24E−1	kg	Measured
Glue	5.00E−2	kg	Estimated
Soap	1.00E−2	kg	Estimated
Truck	2.56E+3	kg/km	Calculated
Output			
Taped pieces	1.00E+0	Set	
Waste tape (landfill)	5.00E−2	kg	Estimated
Truck (collection)	5.25E−1	kg/km	Calculated
Machining			
Input			
Taped pieces	1.00E+0	Set	
Electricity	6.32E+0	kWh	Calculated
Output			
Machined pieces	1.00E+0	Set	
Sawdust	1.84E+0	kg	Estimated
Particulates <2.5 μm, air	1.84E−2	kg	Estimated
Cleaning			
Input			
Machined pieces	1.00E+0	Set	
Cotton towel	2.00E−1	kg	Measured
RAZ water solvent	2.00E−2	kg	Estimated
Truck	1.30E+1	kg/km	Calculated
Output			
Cleaned pieces	1.00E+0	Set	
Waste cotton towel (landfill)	2.20E−1	kg	Estimated
Truck (collection)	2.31E+0	kg/km	Calculated
Assembling			
Input			
Cleaned pieces	1.00E+0	Set	
Plastic pieces	1.50E−1	kg	Measured
Metal pieces	7.20E−1	kg	Measured
Truck	3.91E+3	kg/km	Calculated
Output			
Office cabinet	1.00E+0	Unit	
Packaging			
Input			
Office cabinet	1.00E+0	Unit	
Paperboard	2.50E−1	kg	Measured
Plastic film	5.90E−1	kg	Estimated
Truck	1.67E+3	kg/km	
Output			
Packaged office cabinet	1.00E+0	Unit	

Fig. 3 Life cycle impact assessment of the office cabinet (base scenario). Source: ESM 1 (Table A5), International Reference Life Cycle Data System (ILCD) 2011 methods package
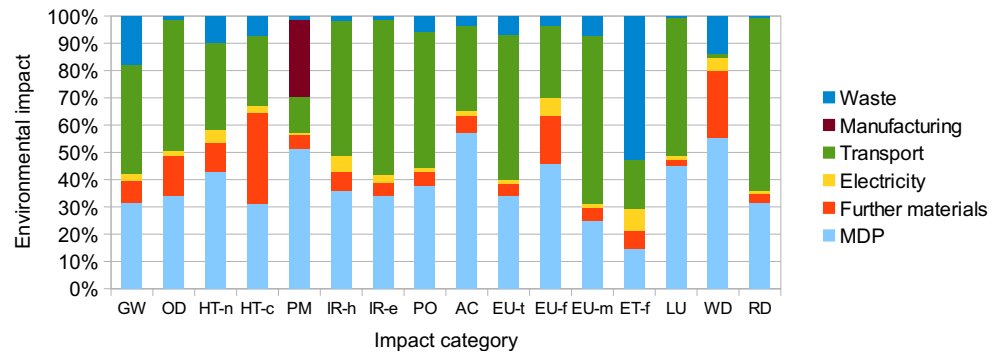
toxicity cancer effects (HT-c), particulate matter (PM), ionising radiation human health (IR-h), ionising radiation ecosystems (IR-e), photochemical ozone formation (PO), acidification (AC), terrestrial eutrophication (EU-t), freshwater eutrophication (EU-f), marine eutrophication (EU-m), freshwater ecotoxicity (ET-f), land use (LU), water resource depletion (WD), and mineral, fossil, and renewable resource depletion (RD). The GW impact is leading the global environmental debate because of its magnitude and potential damage, hence GW was presented in more detail. GW states for GHG impact without biogenic carbon dioxide (CO_2-bio), while GW-total includes CO_2-bio.

3 Results

Process groups represent the environmental impacts of the office cabinet through its life cycle (Fig. 3). The groups are MDP for MDP production; further materials for all inputs used in the manufacturing step, apart from MDP; electricity used in manufacturing step; transport for inputs transport, product delivery, and municipal waste collection; manufacturing for direct emissions from the manufacturing plant; and waste for waste treatment processes. The absolute values of environmental impacts are presented in the ESM 1.

Out of the 16 impact categories evaluated, the pre-manufacturing step presented the highest environmental impacts. The electricity, further material, manufacturing, and waste treatment groups showed smaller relevance compared with MDP and transport groups. In the GW category, the highest impact of the furniture life cycle was from the pre-manufacturing step, particularly the transport of inputs (40%) and MDP production (32%) (Fig. 4).

The substance that contributed most to GW within the office cabinet life cycle was carbon dioxide, particularly due to fossil fuels used in transportation. The biogenic carbon stored in MDP and released via combustion was not accounted for with the GWP method

used in Figs. 3 and 4. It is noticeable that, in order to minimise GW impact, it is necessary to decrease the distances travelled by inputs to the manufacturing plant or switch to less-polluting transportation means. Then, alternative scenarios were proposed to reduce the impacts of the office furniture life cycle.

3.1 Sensitivity analysis

We evaluated scenarios for the product system under study, comparing different fuel use in transportation, shorter distances, or other transportation means for the MDP to examine the potential for reducing environmental impacts of the office cabinet life cycle. The typical Brazilian road truck uses a mixture of 8% biodiesel and 92% diesel, called B8 (Brasil 2014). The biodiesel production considered vegetable oil from soybean as it comprises 77% of national biodiesel production (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) 2016). Thus, four additional scenarios were proposed (Fig. 5a), as follows:

> BS - MDP transported 2100 km by truck with B8 (base scenario);
> T1 - MDP transported 2100 km by truck with 100% biodiesel (B100);
> T2 - MDP transported 645 km from Eunápolis-BA by truck with B8;
> T3 - MDP transported 105 km from Alagoinhas-BA by truck with B8;
> T4 - MDP transported 430 km by truck with B8 and 1733 km by ship with 100% diesel, totalling 2033 km.

WP plants and furniture clusters are strategically located near planted forest areas (Fig. 5). The state of Bahia was the fifth largest area of planted forest in 2014 (Brazilian Tree Industry (IBÁ) 2015), with production higher than consumption (Associação Baiana das Empresas de Base Florestal (ABAF) 2015) and potential to supply the northeast region with WP.
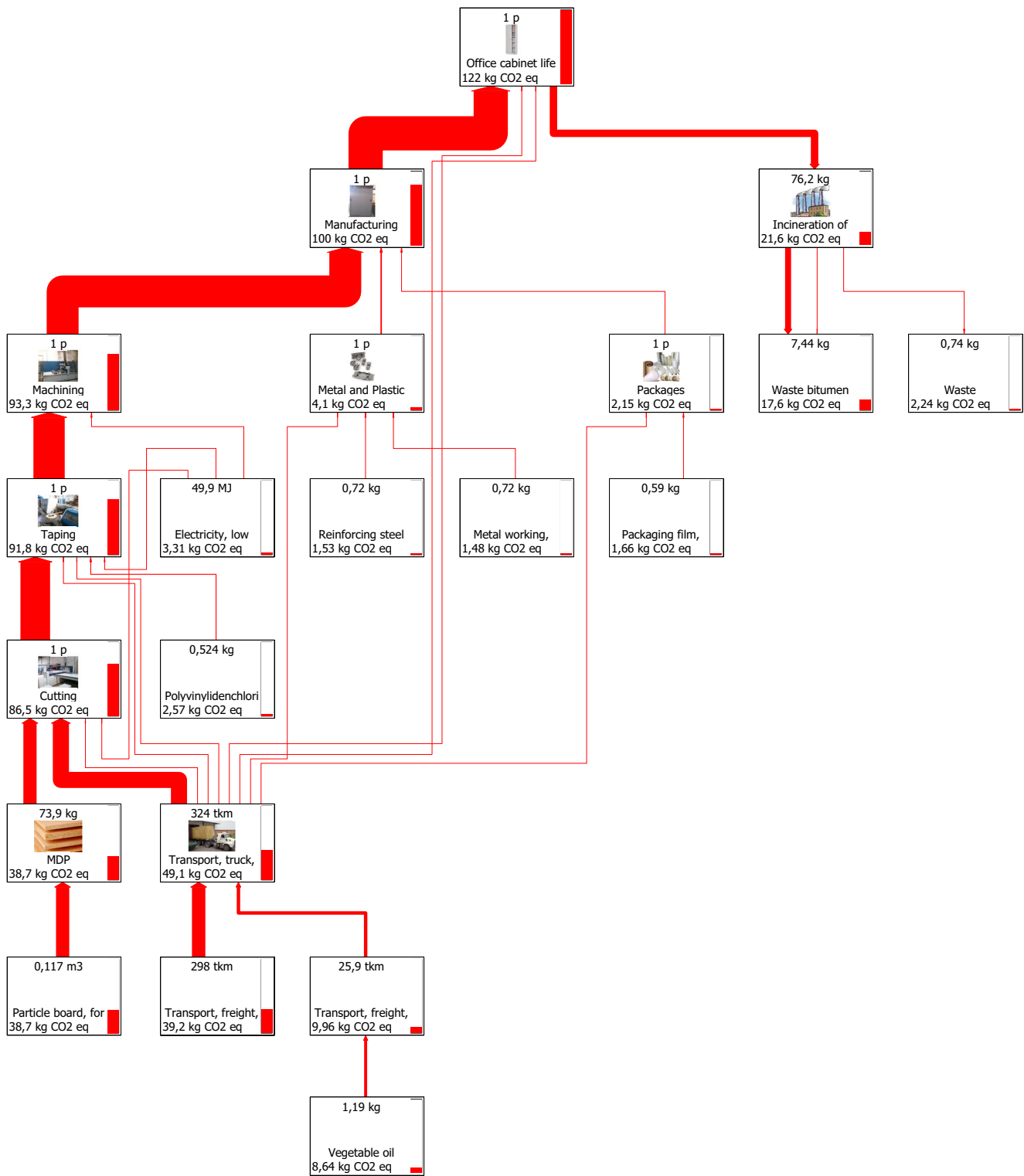
Fig. 4 Process contribution to global warming (GW) of office cabinet life cycle (base scenario). Source: Simapro® 8 software with International Reference Life Cycle Data System (ILCD) 2011 methods package that uses Intergovernmental Panel on Climate Change (IPCC) (2007) 100 years for global warming potential (GWP)

The transport scenarios were proposed based on the fuel switch from B8 to B100 (T1), simulation of a MDP plant installed in the state of Bahia (T2 and T3, Fig. 5b), and the current options of MDP transport from Agudos-SP to Santos-SP port, shipped to Salvador-BA and transported to the manufacturing plant in Lauro de
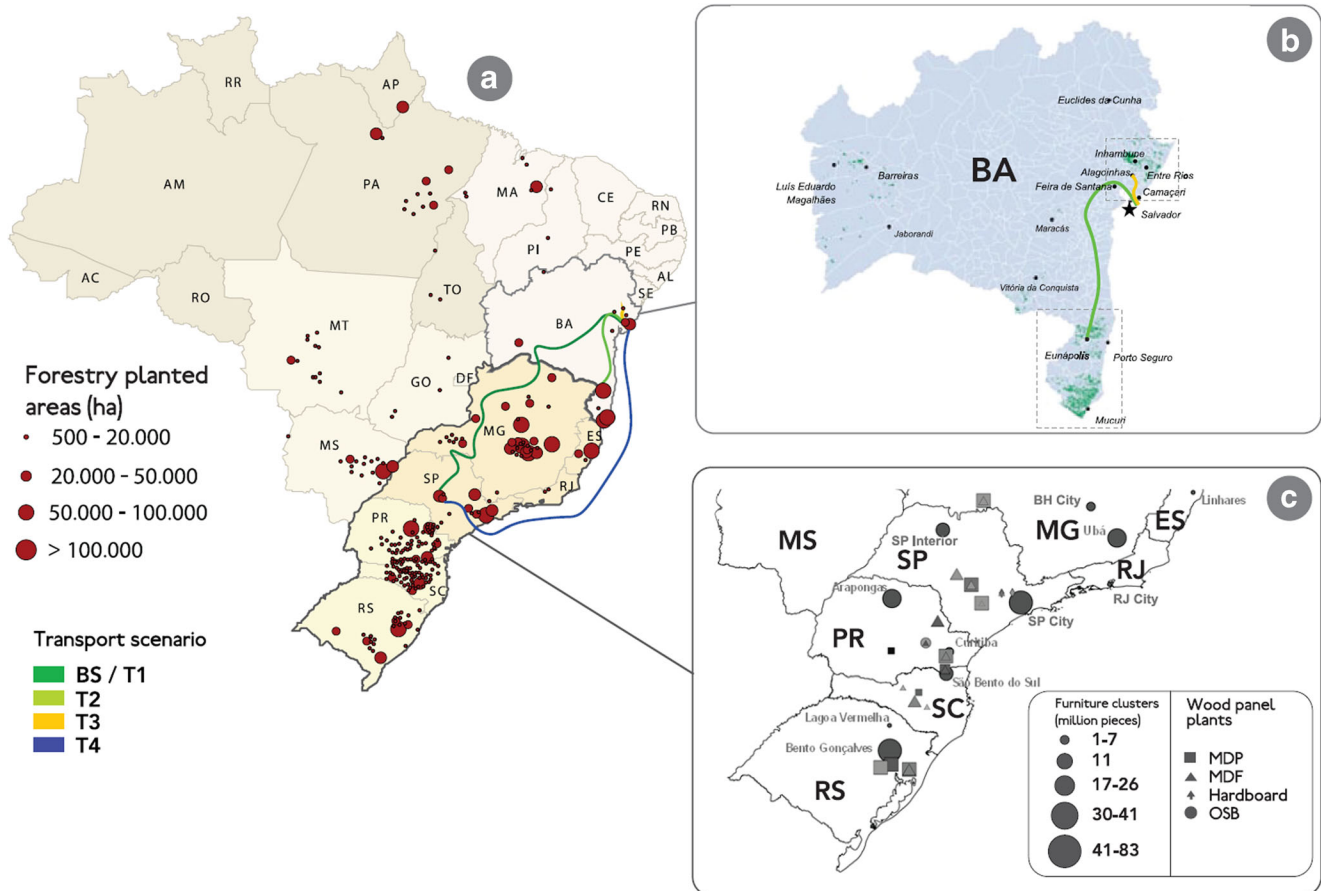
Fig. 5 Transport scenarios of wood medium-density particleboard (MDP). The coloured routes are only for illustration purposes, although the distances used in this study are real ones. Source: Adapted from

Brazilian Association of Forest Plantation Producers (ABRAF) (2013), Vidal and Hora (2014), and Associação Baiana das Empresas de Base Florestal (ABAF) (2015)

Freitas-BA (T4). Fig. 6 shows the environmental impacts of the cabinet life cycle for each transport scenario.

The use of biodiesel for transport in T1 resulted in environmental tradeoffs with larger environmental impacts than in the base scenario, except for OD, HT-n, IR-h, and IR-e, due to Brazilian soybean oil-based biodiesel (Zah et al. 2007). The road distance reduction in T2 and T3, or use of waterways for MDP transport in T4, considerably reduced environmental impacts for all evaluated categories. The WD was little affected as the material production and waste treatment stood out in this category.

It was observed that T3 showed the smallest environmental impacts, followed by T4 and T2. The GW was raised 38% in T1 and reduced 17% in T2, 23% in T3, and 18% in T4, compared with the base scenario. However, the state of Bahia in Brazil does not have a MDP supplier at the moment and so T4 is the most feasible way to reduce the environmental impacts of office cabinet production.

We evaluated the influence of post-use scenarios likely to happen and cut-off rule for the product under study in order to examine the potential for reducing impacts of an office cabinet life cycle (ESM 1 (Tables A1, A2, and A3). Thus, three additional scenarios were modelled, as follows:

BS - post-use step with incineration treatment (base scenario);

LF - post-use step with sanitary landfill treatment;

CO - post-use step with cut-off, whereby no environmental load or credits were considered from product waste;

RW - post-use step with incineration treatment and cut-off for secondary wood material of MDP production, assuming recycled wood from close sources (e.g. 50 km round trip).

RW considers wooden material as burden free (i.e., coming from CO scenario) in order to avoid double counting from the product system that previously generated the secondary resource according to Wernet et al.

(2016). Figure 7 shows the environmental impacts of the office cabinet life cycle for each post-use and cut-off rule scenario.

BS presented larger impacts than LF, except for HT-n, EU-m, and LU. CO reduced the environmental impact considerably, above 20%, only for ET-f compared with the reference BS. RW reduced the impacts considerably in all categories due to secondary wood source for recycled MDP production, except for WD.

The GW was reduced by 10% in LF, 18% in CO, and 42% in RW compared with the reference BS. The absence of fossil carbon dioxide emissions from urea-formaldehyde burning in CO caused 14% GW reduction compared with BS. On the other hand, the substitution of high GHG emission process, such as primary eucalyptus wood, for MDP production in RW reduced GW considerably.

According to Christensen et al. (2009), carbon sequestering and system boundary must be precisely addressed to obtain reliable results for prioritising waste management alternatives. Then, we evaluated the influence of CO_2-bio accounting per group of contribution in the global warming impact of transport, post-use, and cut-off rule scenarios (Fig. 8).

The office cabinet showed a potential to be net GHG sink from wood carbon storage depending on the scenario. BS still has a net GHG sink, while the transport scenario with B100 (T1) is a net GHG emitter in GW-total. The other transport scenarios (T2, T3, and T4) presented benefits in GW-total compared with BS. The post-use of office cabinet with landfill treatment (LF) or secondary material valuation using cut-off (CO) presented the largest net GHG sinks in GW-total. On the other hand, the scenario with recycled MDP (RW) did not count the carbon stored in secondary wood waste share to produce the MDP and presented the worst case in GW-total.

We evaluated the system expansion influence for potential co-products of post-use in different substitution
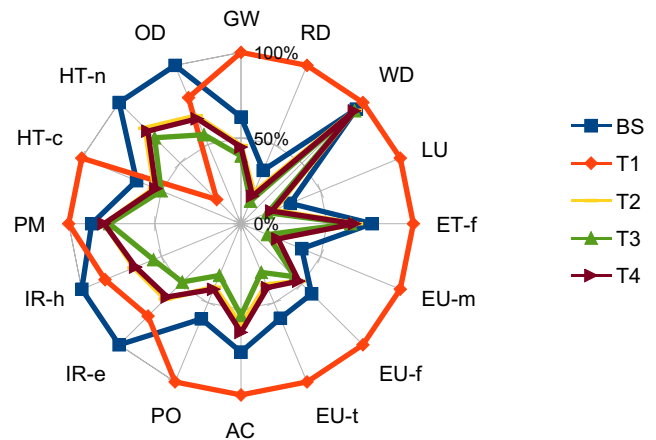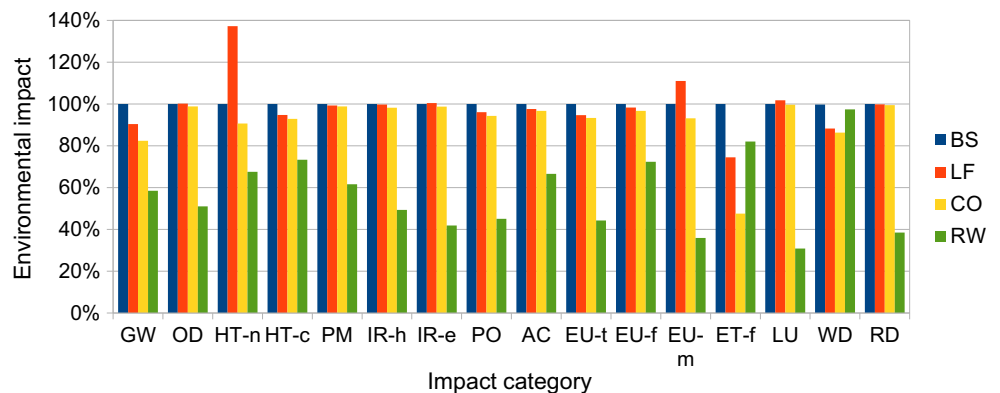

Fig. 6 Comparative environmental impacts of transport scenarios in an office cabinet life cycle. Source: ESM 1 (Table A6), International Reference Life Cycle Data System (ILCD) 2011 methods package

contexts (ESM 1 (Table A4)). Even though ISO 14044 (2006) does not support avoided products (Heijungs 2014), it is a way to keep the product system with one reference flow. Thus, three additional scenarios were modelled, as follows:

BS - post-use step with incineration treatment (base scenario);
IS-w - post-use step with incineration with wood energy recovery substituting thermal energy from wood;
IS-d - post-use step with incineration with wood energy recovery substituting thermal energy from diesel;
RI - post-use step with partial incineration and reuse with MDP, PVC tape, metal parts, and plastic parts substituting their own primary inputs.

The background data of IS-w, IS-d, and RI used ecoinvent database with allocation at the point of substitution (Wernet et al. 2016) to keep consistency with the foreground methodological choices. MDP wastes from

Fig. 7 Comparative environmental impacts of post-use and cut-off rule scenarios in an office cabinet life cycle. Source: ESM 1 (Table A7), International Reference Life Cycle Data System (ILCD) 2011 methods package
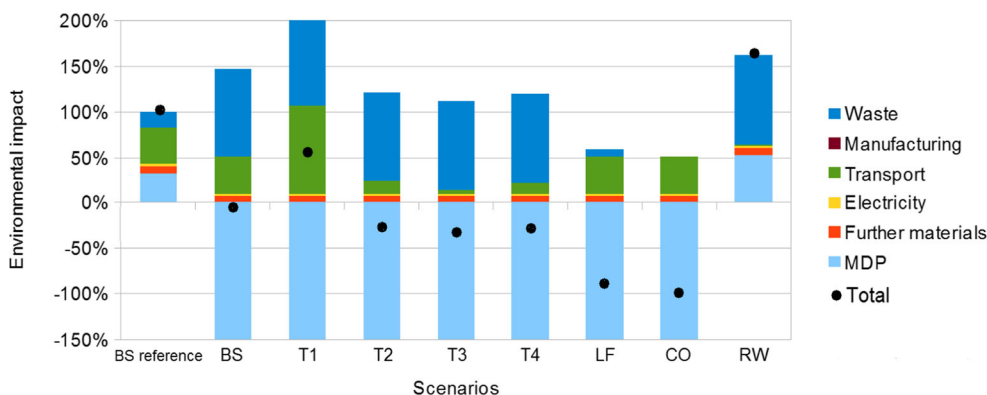
Fig. 8 Comparative global warming (GW-total) impact of transport, post-use and cut-off rule scenarios of the office cabinet life cycle. GW of BS (reference) did not include CO_2-bio. Source: ESM 1 (Table A8), International Reference Life Cycle Data System (ILCD) 2011 methods package that uses Intergovernmental Panel on Climate Change (IPCC) (2007) 100 years for GWP, including biogenic carbon dioxide

manufacturing and post-use steps are 50 and 75 km away, respectively, of the pottery plant to be used as fuel (IS-w and IS-d). On the other hand, the reuse of MDP, PVC tape, metal, and plastic parts in RI consider the materials returning to the manufacturing plant (25 km). The incineration scenarios IS-w and IS-d considered the Lower Heating Value (LHV) of *Eucalyptus* sp. to be 16 MJ/kg of wood (Quirino et al. 2004).

All substitution scenarios reduced the environmental impacts compared with BS as expected (Fig. 9), except for IS-w in WD. However, there is no best substitution scenario overall as every impact category has a dominant one. Some categories such as HT-n for IS-w and OD, IR-h, IR-e, and AC for IS-d presented relative

environmental credits for the office cabinet life cycle. WD in IS-w was a negative impact and therefore it raised the impact when it was subtracted. The higher reductions of IS-w were obtained in HT-n, PO, EU-t, EU-m, and LU arising from avoided wood burning. The IS-d resulted in the highest reductions in GW, OD, IR-h, IR-e, and AC due to avoided diesel burning. The highest reductions of RI were obtained in HT-c, PM, EU-f, ET-f, WD, and RD. RI reduced the environmental impacts considerably as it avoided the largest impact contributions of BS, named production and transportation of MDP.

The GW was reduced by 10% in IS-w, 98% in IS-d, and 58% in RI compared with the reference BS. Therefore, the

Table 3 Comparison of GW impact per kilogram of end product from recent furniture LCA studies

Author	Product	Coverage	GW kg CO_2-eq/kg product	GW-total kg CO_2-eq/kg product
González-García et al. (2011)	Several furniture	Cradle to gate of the manufacturer	0.43–4.84	
González-García et al. (2012a)	Wooden modular playground	Cradle to gate of the consumer	1.40	
González-García et al. (2012b)	Childhood furniture set	Cradle to gate of the consumer	0.95	
Iritani et al. (2015)	Wardrobe	Cradle to gate of the consumer	1.13	
Linkosalmi et al. (2016)	Several furniture	Cradle to gate of the manufacturer	1.49–4.03	−0.08 to 3.37
This study				
Transport				
BS	Office cabinet	Cradle to gate of the manufacturer	1.48	−1.82
T1			2.58	−0.79
T2			1.00	−2.30
T3			0.82	−2.48
T4			0.97	−2.33
Post-use and cut-off				
LF	Office cabinet	Cradle to gate of the manufacturer	1.48	−1.82
CO			1.48	−1.82
RW			0.73	0.93

substitution of highest GHG emission process, diesel thermal energy (IS-d), caused the largest GW reduction.

4 Discussion

The results of this study are in accordance with previous ones, mainly for the GW impact category. In Table 3, the GW and GW-total results of transport, post-use, and cut-off scenarios are presented from cradle to gate of the manufacturer for comparison.

Carbon removal from the atmosphere and temporary storage, for example, in biomass products, has the potential to avoid some radiative forcing and mitigate climate change (Brandão et al. 2013). Then, the carbon storage of wooden products, such as furniture, is a potential GHG sink in the anthroposphere. In fact, Table 3 shows that most products made of renewable materials are not GHG neutral when assessed from a LCA perspective, as reported by Klein et al. (2015). Linkosalmi et al. (2016) identified that one of the eight wooden furniture types (kitchen cabinet) had a biogenic carbon content larger than its GHG emissions. One of the reasons is that the kitchen cabinet was 97% made of wooden materials that had relatively small GW due to few wood processing and short distances of shipment. However, it is very likely that after delivery, use, and post-use steps, the kitchen cabinet turn into a net GHG emitter. The biogenic carbon accounting with the extension from cradle to gate shows how much the results can be biased when comparing global warming impact of products. Wiloso et al. (2016) affirm that dissimilar inventory situations (modes of biomass treatment and valuation) and methodological choices (system boundaries and allocation criteria) can generate various results. The transport scenario shows how a close supplier of wooden material can enhance the net GHG sink of the product. The post-use and cut-off scenarios were not affected due to coverage similarity of inventories from

cradle to gate, except for RW that was penalised by secondary source of wood with no biogenic carbon storage (Table 3).

The distance from most WP plants from the south and southeast regions (Fig. 5c) to the north, northeast and central-west of Brazil, which has only one WP production plant in the state of Pará (Vidal and Hora 2014), increases the freight costs and environmental impacts. The manufacturing plant manager (personal communication) said that the transportation cost of a MDP batch in T4 is R$ 5500 compared with R$ 7500 in the base scenario, Brazilian Real currency. However, oceanic shipping is slower than road transport, although this is a disadvantage that can be solved with better production planning. Then, it is observed that T4 is better in the environmental and economic aspects, which strengthens the furniture manufacturing plant in the pursuit of sustainability.

The furniture post-use scenario can have a significant influence in the environmental profile of a product (Cordella and Hidalgo 2016). Contrary to some authors (González-García et al. 2011, 2012a, b; Iritani et al. 2015; Linkosalmi et al. 2016), the environmental impacts of post-use step were representative, above 5% of the impacts in base scenario, for GW (18%), HT-n (10%), HT-c (7%), PO (6%), EU-t (7%), EP-m (7%), ET-f (53%), and WD (14%). LF reduced representatively the environmental impacts in GW (10%), HT-c (5%), EU-t (5%), ET-f (26%), and WD (12%), although it raised HT-n (37%) and EU-m (11%). Therefore, landfilling is not the worst option for furniture waste treatment as Cordella and Hidalgo (2016) mentioned. The post-use step could double the GHG emissions of a biomaterial or reduce it up to claim carbon neutrality (Glew et al. 2017). LF seems a carbon storage option of wooden materials (Fig. 8) as the ecoinvent database (Doka 2009) considers that up to 3% of the carbon from wood are ever emitted as landfill gas (Micales and Skog 1997). The biogenic carbon that is not mineralized is stored within the

Fig. 9 Comparative environmental impacts of substitution scenarios of the office cabinet life cycle. Source: ESM 1 (Table A9), International Reference Life Cycle Data System (ILCD) 2011 methods package
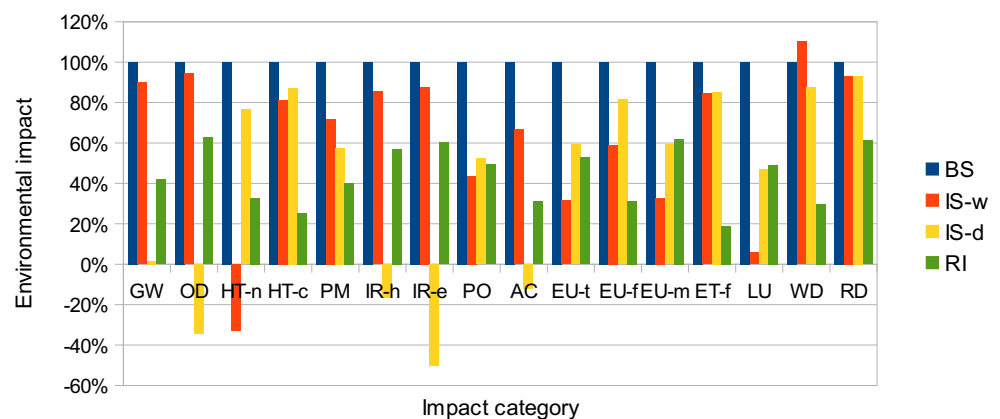
landfill such as lignin that is essentially recalcitrant and a fraction of cellulose and hemicellulose not converted to carbon dioxide and methane (De La Cruz et al. 2013). Ximenes et al. (2008) identified that no significant loss of dry mass was measured in wood products landfilled for 19 and 29 years but 8.7% for hardwoods buried for 46 years. Regarding WP, Wang et al. (2013) presented carbon losses only for landfill operation of 1.5 and 2.5 years. Therefore, carbon accounting of biogenic waste is critical to keep consistency and transparency in LCA (Morris 2016). A robust assessment of global warming impact requires a dynamic LCA approach of all GHG emissions (positive) and sequestration (negative) through time (Levasseur et al. 2013) with specific characterisation factors for biogenic carbon dioxide releases (Guest et al. 2013).

The cut-off rule scenarios showed larger environmental gains for recycled MDP (RW) than the valuation of MDP at post-use (CO), except for GW-total where RW did not benefit from biogenic carbon storage. The choice of allocation criteria can have significant implications for life cycle studies (Johnson et al. 2013) as shown in scenarios CO and RW. The contribution of system expansion varies with the waste management, favouring the substitution context of material and energy recovery (Fig. 9).

Short-term solutions bring considerable environmental and economic benefits to furniture product systems. However, the path to further reduce the environmental impacts involves more complex solutions in the medium and long term, such as environmentally cleaner materials (Silva et al. 2014), improvement of manufacturing technology (Höglmeier et al. 2015), efficient transport modes, cleaner fuel, and post-use material reclamation (Susanty et al. 2016). The complexity of product systems in all sectors claims to benefit all supply chains involved in a product life cycle. Actions to promote longer material utility life (e.g., cascading) and reverse logistics are seen as promising (Höglmeier et al. 2015) such as CO and RW. In terms of the idle capacity of transport (the empty return journey for trucks and ships), cleaner fuels (although T1 with B100 was not the case) or shorter distances (T2 and T3) and cleaner transport modes (T4) for material supply and waste collection would enable a green supply chain management practice in the furniture industry.

Some limitations of this study are that function and lifetime are essential elements to compare furniture products (Cordella and Hidalgo 2016) in Table 3, though service life of furniture is difficult to predict (Linkosalmi et al. 2016). The environmental performance of products or services is proportional to their lifetime that can be extended by material quality, design, and maintenance (Souza et al. 2017). Furthermore, comparison of product carbon footprints should be supported by parameter uncertainty estimates (Henriksson et al. 2015). The reduction of volatile organic compounds from resins is one priority for attaining sustainable development in the furniture industry (Azizi et al. 2016), and this issue should be afforded more attention in the use step. Nevertheless, the current study used average data from ecoinvent for WP production in Brazil (Silva et al. 2013). Furthermore, the dataset for MDP production did not include surface coating materials that contribute a small fraction to the environmental impacts (Linkosalmi et al. 2016). Moreover, this article presented how the environmental LCA and unit costs provide a basis for decision-making involving environmental improvements and product competitiveness.

The implementation of Circular Economy worldwide seems in its infancy, mainly focused on recycling rather than reuse (Ghisellini et al. 2016). It was presented that reuse and recycling scenarios struggle with methodological choices that are a source of uncertainty according to Beltran et al. (2016). Therefore, showing many possible scenario combinations is a way to reduce biased results (Beltran et al. 2016) such as the ones presented for waste management, allocation criteria, biogenic carbon accounting, and substitution contexts. A protocol to practice uncertainty and sensitivity analysis in the field of LCA such as that which is done by the risk analysis community would be helpful (Cucurachi et al. 2016).

5 Conclusions

In this article, we assessed the serial manufacturing of an office cabinet in a medium-sized industrial plant in order to propose environmental improvements. It was found that in the modern furniture manufacturing industry, most of the environmental impacts occur outside the plant, except for particulate matter. The production and transportation of the main input, the wood MDP, had the largest environmental impact.

In order to reduce such impacts, transport scenarios were proposed with truck fuel switches, reduction of travel distance by truck, and the use of two transport modes (truck and ship). The oceanic shipping presented lower environmental impacts than the base scenario or fuel switch scenario, but it requires production planning due to time constraints. The best scenario was the MDP production in the state of Bahia, which is closer to the locations of manufacturing and use in the product life cycle. The waste management and methodological choices were relevant for environmental impact scores. Furthermore, if the utility of MDP was extended by reuse, recycling, or energy recovery, the environmental impacts would be even lower. Biogenic carbon accounting was decisive to claim carbon neutrality of a product. In addition, the substitution context of waste material valuation can influence the relative benefits of the potential co-products.

It is recommended that scenarios with environmentally friendly inputs are evaluated in the production of MDP, along with other types of fuels in transport, reduction of particulate matter emissions in manufacturing, and substitution of raw materials by wood waste in order to enhance the ecological profile and net GHG sink of wooden furniture.

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