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ENVIRONMENTAL PROFILE ANALYSIS OF MDF PANELS PRODUCTION: STUDY IN A BRAZILIAN TECHNOLOGICAL CONDITION

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ABSTRACT: The main goal of this study was to analyze the environmental profile of MDF panel manufacturing in the Brazilian industry in terms of energy, emissions and dependence on renewable sources. The study was conducted by using the methodology of Life Cycle Assessment (LCA), specifically through the development of the first Life Cycle Inventory (LCI) of MDF in a Brazilian industry. The life cycle inventory and the production processes analysis were constructed using Umberto® v.5.6 software and following the ISO 14040 series. The study covers the life cycle of MDF production from gate-to-gate perspective, involving the on-site manufacturing system. The functional unit was defined in 1 m³ of MDF. About 76% of energy required to produce MDF is thermal (52.8% of thermal energy is required for the drying process of wood fiber). CO₂ is a major emission during the MDF production, where natural gas contributes to 96.7% of total CO₂ fossils. It was observed a low dependence of non-renewable source (19.2%) compared with the literature.

ANÁLISE DO PERFIL AMBIENTAL DA PRODUÇÃO DE PAINÉIS MDF: ESTUDO EM UMA CONDIÇÃO TECNOLÓGICA BRASILEIRA

Palavras chave:
Desempenho ambiental
Inventário do ciclo de vida
Painel de madeira reconstituída
Sustentabilidade
Tecnologia de sistema de produção

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RESUMO: O principal objetivo, neste artigo, é analisar o perfil ambiental da produção do painel de madeira MDF produzido em uma indústria brasileira em termos de energia, emissões e dependência de fontes renováveis. O estudo foi baseado na metodologia de Avaliação do Ciclo de Vida (ACV), especificamente por meio do desenvolvimento do primeiro Inventário do Ciclo de Vida (ICV) do MDF de uma indústria brasileira. O Inventário do Ciclo de Vida e a análise dos processos produtivos foram construídos utilizando o software Umberto® v.5.6, atendendo aos requisitos normativos da série de normas ISO 14040. O estudo abrangeu o ciclo de vida da produção do MDF na perspectiva *gate-to-gate*, envolvendo os limites *in-loc* da planta fabril. A unidade funcional adotada foi 1 m³ de MDF. Cerca de 76% da energia requerida para a produção do MDF é de origem térmica (onde 52,8% é demandada pelo processo de secagem da fibra de madeira). O CO₂ é a maior emissão observada durante a produção do MDF, na qual o gás natural contribui com 96,7% do total de CO₂ de origem fóssil. Foi observada uma baixa dependência de fontes não renováveis (19,2%) quando comparada à literatura.

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INTRODUCTION

Impacts associated with forest-based products and their production systems are being researched by various science field. In the context of modern industry, Life Cycle Assessment (LCA) is an important method to environmental management (LÖFGREN et al., 2011) and evaluates environmental performance of the product, process or pathway along its partial or whole life cycle. Hence, LCA is a useful tool to analyse the environmental profile of Medium Density Fiberboard (MDF) production.

From the 1990s on, efforts were done in order to analyze the environmental performance of forestry products through LCA methodology application (RIVELA et al., 2007). On the other hand, wood panels began to be studied only in the late 2000s. Studies (BENETTO et al., 2009; GONZÁLEZ-GARCÍA et al., 2009; RIVELA et al., 2006) about the environmental impact of wood panels, particularly the medium-density fiberboard (MDF) were developed in the USA (WILSON, 2010), Canada (ATHENA SUSTAINABLE MATERIALS INSTITUTE, 2009) and Europe (RIVELA et al., 2007; WASTE & RESOURCES ACTION PROGRAMME - WRAP, 2009) in order to provide the environmental information about the panel, evaluate their impacts, propose improvements in the production system, direct scientific studies focusing on reducing environmental impacts and, finally, to promote innovation. Notwithstanding the diverse benefits of LCA, there have been some difficulties to disseminate this methodology in Brazil mainly by the lack of Life Cycle Inventories (LCI) (RIBEIRO; SILVA, 2010).

The aim of this paper was to analyze the environmental profile of MDF manufacturing in a Brazilian industry in terms of energy, emissions and dependence on renewable sources. To analyze the environmental aspects, this paper presents the first reported LCI of Brazilian MDF, based on its technological conditions.

MATERIALS AND METHODS

The study was developed in compliance with the ISO series 14040 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS - ABNT, 2009a, 2009b) and current state of the art LCA practices (UNITED NATIONS ENVIRONMENTAL PROGRAMME - UNEP, 2011). The software Umberto® v.5.6 Acad. was used for calculations.

Goal and scope definition

This study aims to develop high-quality data (Life Cycle Inventory – LCI) on the environmental profile

of MDF in the Brazilian industry in order to analyze its environmental profile. A Brazilian MDF industry with an approximate process production of 300,000 m³ per year and considered representative of the 'state of the art' was selected to study the process in detail. The industry of this study belongs to one of the largest business group manufacturer of reconstituted wood panels in Latin America, this fact justifies the selection of the company. The study covers the life cycle of MDF manufacturing (gate-to-gate plant system), documenting all inputs and outputs.

Functional unit

The functional unit provides a reference to which all inputs and outputs are referred (ABNT, 2009a). The volumetric unit is adopted as reference to recorded on-site production data and was used as a functional unit in previous wood panel studies (ATHENA..., 2009; RIVELA et al., 2007; WILSON, 2010; WRAP, 2009). Therefore, all flows, materials, and emissions were expressed as a function of the functional unit: 1.0 m³ of finished MDF, oven-dried and without decorative coatings. For those LCA practitioners who conduct studies based on mass, 1.0 m³ of MDF studied weights 683.2 kg (on oven-dried mass).

Description of production process and system boundary

Medium Density Fiberboard (MDF) is an engineered wood product formed by breaking down softwood into wood fibers, often in a defibrator, combining it with wax and resin, and forming panels by applying high temperature and pressure. It is a building material similar in application to plywood but it is made up of separated fibers, not wood veneers. MDF has a typical density of 600–800 kg·m⁻³ and similar manufacturing processes are used in all MDF industries around the world.

The MDF manufacturing process is highly automated, process-controlled, and fairly linear. Figure 1 illustrates the on-site process of the industry studied. The process consists of the following steps identified in Table 1.

Data collection, data quality analysis and calculations procedures

The collection of high quality primary data is fundamental to make a reliable analysis. All data were

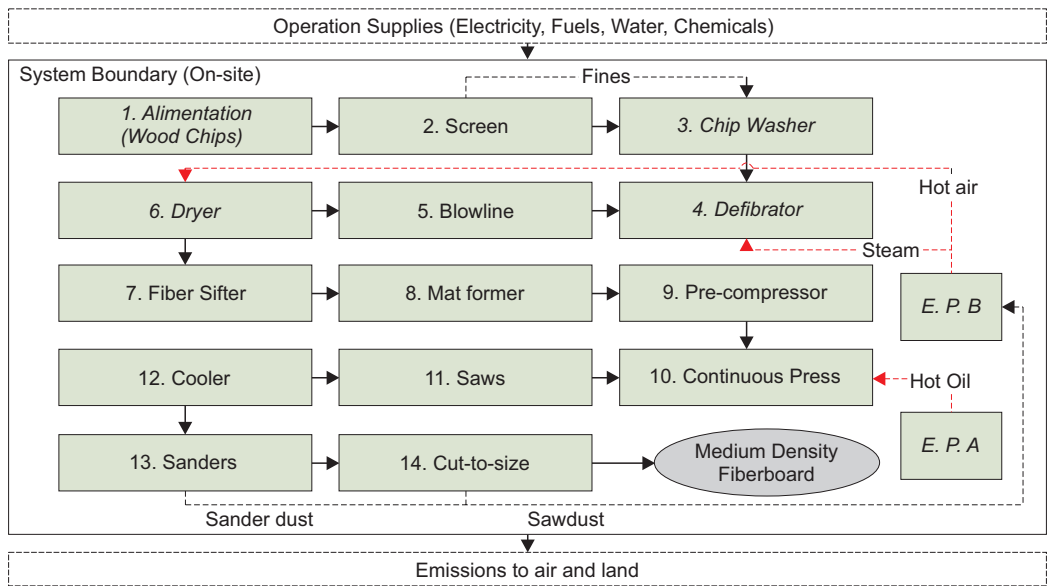


FIGURE I Flow Sheet of MDF Manufacturing System.

FIGURA I Diagrama de Fluxos do Sistema de Produção do MDF.

TABLE I Description of MDF production process.

TABELA I Descrição dos processos produtivos do MDF.

Description of production process	
Alimentation	The wood chips are delivered to the mill by truck. The chips are made of pine and eucalyptus (88% and 12%, respectively), and are stored in the wood yard, without being covered. A Chip Reclaimer pull the wood chips to process, where the same shall be replaced by a measurement thread (Metering Screw) to homogenize the amount of material that goes to the chip screen through belt conveyor. The moisture content of the chips can range from 40 to 70% on an oven-dried weight basis. Annually, are consumed approximately 220,000 tons of wood chips.
Screen	Small Particles (Fines) and Large Particles/Peel (Oversized) are removed from the chips during the screening. The Fines returns to the processor and the oversized are sold as biomass to another mill. Approximately 6% of the total chips that pass through the screen are destined as fines whereas 0.5% as oversized. Only the appropriate sized chips are fed to Chip Wash.
Chip Washer	The chips are washed to remove dirt. The residues and extracted materials are treated as effluent through a centrifuge on the mill. During washing, the first part is the Scrap separator where a rotating wheel with paddles ensures that all chips will be submerged and the scrap is separated and discharged into a conveyor drainer. The chips goes to a tank where it will be pumped to Screw drainer.
Defibrator	After washing, the fines return to process mixing with the chips in conveyor mixer. A level control device measures the amount of material is fed in steaming bin and sends signal to metering bin to request more or less chips or fines. After steaming bin, the transfer screw takes the material until plug screw which removes the extractives and water excess from the chips. The chips are softened in a steam-pressurized digester (pressure between 1–9 bar) and then transported into a pressurized refiner chamber. The heated wood chips are then refined, a process of mechanically reducing it into fibers by shearing the wood between two rotating metal disks that separate the fibers; this process is accomplished by the use of a pressurized disk refiner. The average consumption of steam is 0.5 kg of steam per kg of fiber produced.
Blow line	In this process, resin and other additives are blended with the fibers. Friction and contact between fibers may help to distribute the resin. The resin used is based on Urea-Formaldehyde (UF) and are consumed 65.6 kg·m ⁻³ of MDF. In this process is also added wax in wood fibers (3.4 kg·m ⁻³ of MDF produced), urea (0.8 kg·m ⁻³ of MDF produced) and urea scavenger (that allows to control the emission of free formaldehyde of resin, 4.7 kg·m ⁻³ of MDF produced).
Dryer	The fibers drying occur in tube dryer of hot air, where the hot air is responsible for drying the fiber. The hot air stream evaporates the moisture and conducts the fiber. The hot air dryer is generated by the power plant, usually by combustion of wood dust generated by the mill or eventually by natural gas.

To be continued...
Continua...

TABLE I Continued...

TABELA I Continuação...

Description of production process	
Fiber Sifter	After drying, the fibers (7-9% moisture content) pass through a wind filter (Sifter). The sifter is used to remove clumps of fibers or other heavy materials that may cause problems to the process and the final product. The dry fiber is selected and delivered to the mat former.
Mat former	The dry and selected fiber goes to a feeder bin with a uniform distribution through the action of pendulum fiber distribution. The fibers are uniformly distributed by former and become a mat fiber.
Pre-compressor	The mat fiber cross the deaerator (to remove air between the fibers) and, finally, the mat is pre-compressed by the compressor. The mat is moistened with its upper and lower surface during the formation process to be pressed. The water used to humidify the mat is represented in 2.5 L·m ⁻³ of MDF produced.
Continuous Press	The continuous press operates as a function of temperature and pressure. Press operates at about 170–230°C and 5.2 MPa in a sufficient time to cure the resin and at a pressure to consolidate the mat to a desired density, thereby controlling the physical properties of the panel. The continuous press is heated by hot oil generated in the thermal plant. As a consequence of temperature rise is the emission of particulates and the release of free formaldehyde (H ₂ CO). The continuous press produces annually about 300,000 m ³ of MDF panel with thickness from 5.5 mm to 30 mm.
Saws	The diagonal saw cuts the panel in the transverse direction The panels produced by the continuous press are cut into three parts for commercialization.
Cooler	The MDF goes first to a cooler, where it stays for 40 min. After that, the produced panels remain resting for 48 h so that their physical and mechanical properties are stabilized.
Sanders	Panels are sanded on both major surfaces to acquire the proper thickness and smoothness. Sander dust coming off this process is recycled back into the manufacturing process to be used as fuel for the thermal plant. Approximately 7.4% of the material is removed by the action of sandpaper. About 74.8% of dust generation comes from the sanders action.
Cut-to-size	The large panels are sawn to dimensions of panel width and length. Panel trim is hammer milled into particles and sent back into the processor. All the sawdust is sent back to the processor in the thermal plant. Approximately 7.4% of the material is removed by the sandpapers action. About 74.8% of dust generation comes from the action of sanders.
Energy Plants (E.P)	It consists of two Thermal Plants. The first (E.P. A) is responsible for heating the hot oil used in the continuous press where its fuel is natural gas. The E.P. A produces around 0.187 MWh of hot oil per m ³ of MDF produced. The second (E.P. B) provides steam and hot air to the processor, where its main fuel is biomass (sawdust from the process and purchased from other plants) and occasionally it also use natural gas as fuel. The E.P. B generates about 15 Gcal·h ⁻¹ to hot air in dryer process and 10 Gcal·h ⁻¹ in steam to defibrator process.

related to inputs and outputs of the MDF manufacturing in a Brazilian mill during a one year period (2010). The data was collected through questionnaires. The questionnaires were developed based on two models: i) Questionnaire developed by the Athena... (2009) for the Life Cycle Assessment (LCA) of the Canadian MDF, which follows the methodology proposed by the ISO 14040 series and; ii) Sheets of collection data suggested by the ISO 14044 (ABNT, 2009b).

Data was collected from managers responsible for each specific area and the treatment of this data was performed by analysis of the LCI. The assessment of the quality of LCI had been carried out using the methodology provided in Umberto® v. 5.6 Acad., which is adapted from UNEP (2007). The Umberto® software was used to model, calculate, and visualize material and energy flow systems.

The procedures for calculating the LCI involved the mass and energy balances of the process defined at the boundary on-site. Inputs and outputs of materials and energy for each elementary process were quantified. It was defined for the units “kg” and “MJ” for mass and energy balances, respectively. All data was computed in dry mass. A mass balance considering all inputs materials and all outputs of products and emissions had a difference of 0.41% that is suitable within the maximum 5% balance required in the literature (RIVELA et al., 2006; WILSON, 2010).

Emission inventory data about MDF processes was developed using primary and secondary sources. The primary data was collected directly from the industry. For diesel used in chips transportations, the emissions data (secondary source) was inventoried from bibliographic data (BAUER, 2007; SCWAIGER; ZIMMER, 2001) (Table 2).

TABLE 2 Secondary data sources used.**TABELA 2** Fontes de dados secundárias utilizadas.

Activity Area	Compound emitted	Emission factors	Unit	Reference
Alimentation	CO ₂	9.04	g·MJ ⁻¹ fuel	Bauer (2007)
	CO	0.0435	g·MJ ⁻¹ fuel	Bauer (2007)
	N ₂ O	0.02	g·MJ ⁻¹ fuel	Schwaiger and Zimmer (2001)
Transportation of chips (Diesel used ¹)	CH ₄	0.013	g·MJ ⁻¹ fuel	Bauer (2007)
	NO _x	0.108	g·MJ ⁻¹ fuel	Bauer (2007)
	NM VOC	0.0378	g·MJ ⁻¹ fuel	Bauer (2007)
	SO ₂	0.0139	g·MJ ⁻¹ fuel	Bauer (2007)
	Pb	3.00 E-06	g·MJ ⁻¹ fuel	Bauer (2007)

¹Specific characteristics of diesel: Density = 0.85 Kg·L, Higher heating value (HHV) = 36.23 MJ·Kg.

In MDF manufacturing process, the energy balances are done mainly to determine the expected energy consumption to remove the desired amount of water from the wood fibers during processing (WILSON, 2010). The average Moisture Content (MC) of wood material coming into the mill in this study was 54.12% on an oven-dry weight basis. The targeted MC for the dried material with resin applied was 6 – 10%, in mat formation. The MC of the finished MDF was approximately 7.3% on an oven-dry. The average thickness of the panels produced was 16 mm and the average density was 683.2 kg·m⁻³ on an oven-dried weight basis.

RESULTS AND DISCUSSION

The data related in this paper form the scientific analyse of environmental profile of MDF manufactured in the Brazilian industry. The company's production capacity is approximately 300,000 m³ of MDF per year and its production system is the same and it is in consonance to researched and reported by Banco Nacional de Desenvolvimento Econômico e Social - BNDES (2010) in the study of Brazilian wood panels industries. Therefore, in general this study is representative for the MDF Brazilian industry.

Furthermore, the MDF production process reported in this paper is also similar to the world

technology state-of-art for the MDF manufacturing described by Rivela et al. (2007).

In this context, the life cycle inventory (LCI) was done and analysed in terms of emissions, energy and dependence on renewable sources. The LCI can be used as evidence to the environmental impacts of MDF (future LCA studies) and to be a part of the decision-making process towards environmental issues such as sustainability, green building, green purchasing, carbon storage, climate change, eco-innovation and eco-design.

Life cycle inventory

All inputs and outputs for the on-site manufacture of MDF were obtained from the industry and the inventory data of the MDF manufacturing system that are shown in Table 3. The inputs produced 1.0 m³

TABLE 3 On-site inputs and outputs for 1.0 m³ of MDF.**TABELA 3** Entradas e Saídas para 1,0 m³ de MDF.

Production data	Unit	Unit·m ⁻³
Inputs		
Wood ^a		
Chips (Eucalyptus)	kg	80.7
Chips (Pinus)	kg	617
Chemicals ^b		
Wax	kg	3.4
Urea-formaldehyde resin	kg	65.6
Urea scavenger	kg	4.7
Ammonium Sulfate	kg	0.1
Urea	kg	0.8
Electricity		
Electricity	MJ	1009.7
Fuels		
Natural Gas	m ³	17.4
Diesel	L	0.4
Sawdust (purchased)	kg	87.4
Sawdust (in-mill generated)	kg	80.22
Water Use		
Water (on-site treated)	L	110.4
Artesian Water	L	22.1
Outputs ^a		
Medium Density Fiberboard (MDF)	kg	683.2
Bark mulch (sold)	kg	3.5
Wood waste (sold)	kg	4.3

^a Wood and Bark weights given as oven dry.

^b Chemicals weights at 100% solids.

of MDF (683.2 kg) and consisted of 697.7 kg of wood chips on an oven-dry weight basis, resin, scavenger, wax, and ammonium sulfate. Electricity, water, and fuels are also necessary in on-site system boundary to produce the MDF. The emissions are listed separately (Table 4).

TABLE 4 On-site outputs for 1.0 m³ of MDF.

TABELA 4 Saídas para 1,0 m³ de MDF.

Emissions data	Unit	Unit·m ⁻³	%
Outputs			
Medium Density Fiberboard (MDF)	kg	683.2	
Emissions to air			
Carbon Dioxide, CO ₂ (fossil)	kg	34.7	76.9%
Carbon Monoxide, CO	kg	4.5	10.0%
Nitrogen Dioxide, N ₂ O	kg	2.17	4.8%
Methane, CH ₄	kg	1.6E-3	4E-3%
Nitrogen oxides, NO _x	kg	1.27	2.8%
Total VOCs	kg	1.12	2.5%
Particulate	kg	0.6	1.3%
Sulfur Dioxide, SO ₂	kg	0.04	0.1%
Lead, Pb	kg	3.9E-7	1E-6%
Formaldehyde, H ₂ CO	kg	0.5	1.1%
Sulfuric Acid, H ₂ SO ₄	kg	0.12	0.3%
Sulfur Oxides, SO _x	kg	0.12	0.3%
Emissions to land			
Boiler Fly Ash	kg	1.9	42.2%
Wood waste	kg	2.6	57.8%

^a Wood and Bark weights given as oven dry

^b Chemicals weights at 100% solids

The main MDF raw material is wood, in a ratio of 88% of total wood for pine chips and 12% of eucalyptus chips. In Brazil, the wood for the MDF manufacturing is provided exclusively from dedicated forests. Nevertheless, there are recent studies that have been analyzed the addition of waste to produce wood panels in Brazil (BARROS FILHO et al., 2011; SILVA et al., 2012). According to Silva et al. (2013), unlike that in Brazil, in the USA and Europe the wood used to produce wood panels is mostly waste wood (preconsumer, e.g., from forest operations and sawmills, and postconsumer).

It can be noted that urea-formaldehyde resin (UFR) is the chemical most used to produce MDF. The UFR bind the wood fibers together and guarantees good physical-mechanical properties of the panel. The scavenger is used as an additive to capture excess of formaldehyde emissions during the press process of MDF panel.

The water system of the MDF industry is a closed loop system. Therefore, emissions to water are not included in this study. For 1.0 m³ of MDF, were used 110.4 L of water by Water Treatment Plant (WTP) and 22.1 L from artesian water. Bark mulch and wood wastes generated in the MDF process were delivered to be sold as a biomass for others industries. Additionally, there were generated boiler fly ash (1.9 kg·m⁻³) and wood wastes (2.06 kg·m⁻³) that were sent to be used as composting for agriculture.

Values reported in table 4 summarized average values of emissions from the on-site MDF Brazilian industry. Similarly to the literature (WILSON, 2010), the air emissions of Brazilian MDF process are generated due to three reasons. The first is caused by mechanical processing of wood that can result in particulate wood emissions of various sizes. The second is caused when wood and resin are exposed to elevated temperatures during the pressing and drying process. The last reason refers to the combustion of fuels as wood, diesel, and natural gas.

For this particular industry, the total energy demand required for the production of 1.0 m³ MDF is 4320 MJ. Table 5 presents the inventory of energy for the production of 1.0 m³ of MDF studied.

The energy for the MDF production results from sources of electricity, wood, natural gas, and hot oil, while diesel fuel is responsible for powering transport in the plant. The interpretation and analysis of energy aspects are laid out in sequence.

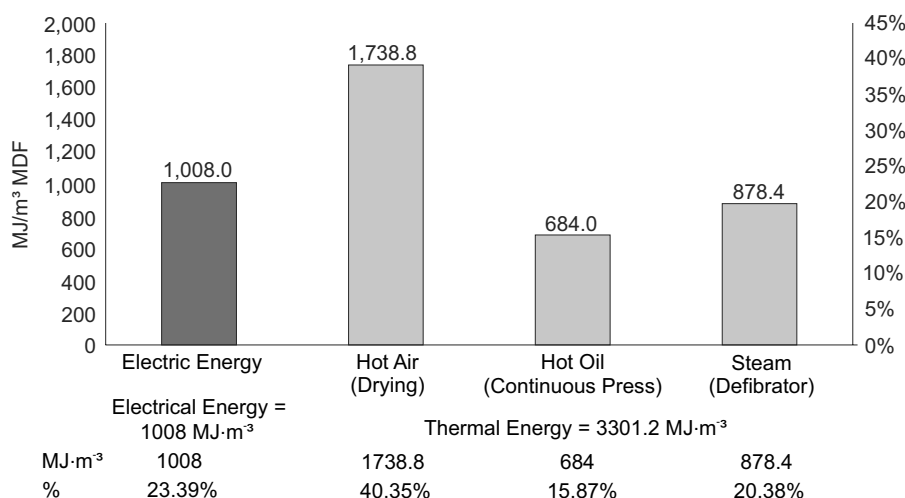
Energy analysis

Electrical power is used all over the manufacturing process in order to operate equipment inside the plant, such as conveyors, grinders, fan motors, hydraulic motors, and sanders, among others. The thermal energy is generated by two energy plants. The Energy Plant A (E.P. A) is responsible for the heating of the hot oil used in the continuous press where its fuel is natural gas. The second, Energy Plant B (E.P. B) provides steam and hot air to the process, where its main fuel is biomass (Sawdust from the processor and purchased from other plants) and occasionally it also burns natural gas as fuel. Figure 2 illustrates the total electric power demand compared to the consumption of thermal energy at the specific elementary processes.

Approximately 76% (3301.2 MJ·m⁻³) of the demand for energy is thermal, where 40% (1738.8 MJ·m⁻³) comes from thermal energy required for drying fibers

TABLE 5 Energy Inventory to produce 1.0 m³ of MDF.**TABELA 5** Inventário de Energia para produção de 1,0 m³ de MDF.

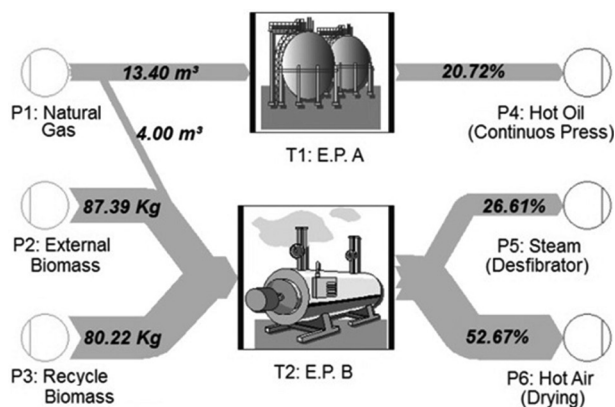
Energy data	Unit	Unit·m ⁻³	MJ·m ⁻³	% Relative	Energy data	Unit	Unit·m ⁻³
Inputs					Outputs		
Electric Energy	KWh	0.28	1008	23.3%	MDF	kg	683.2
Natural Gas	m ³	17.40	684	15.8%	Boiler Fly Ash	kg	1.9
Diesel Oil	L	0.41	10.8	0.3%	Wood Waste	kg	2.6
Wood Dust (Purchased)	kg	87.39	1368	31.7%			
Sawdust (Generated in mill)	kg	80.22	1260	29.2%			
Sanding Dust	kg	50.27	936	21.7%			
Sawdust	kg	29.95	324	7.5%			
Total	-	-	4330.8	100%			

**FIGURE 2** Energy Demand in MDF production: Electrical versus Thermal Energy.**FIGURA 2** Demanda de Energia na Produção do MDF: Energia Elétrica versus Térmica.

(hot air dryer). The demand for electricity represents 24% (1008 MJ·m⁻³) of the total energy demand. The energy plant responsible for the generation of steam and hot air (E.P.B) is operated with the combustion of natural gas and wood fuel (sawdust). Figure 3 represents the contribution of each energy source used in each energy plant (E.P.A and E.P.B) to generate a 1.0 m³ of MDF in the period studied.

The sawdust purchased (External Biomass) and the sawdust generated (Recycle Biomass) accounts for 91.7% of the total heat generated by E.P.B. The burning of natural gas represents 8.3% of the total thermal energy generated in this energy plant.

This means that less than 10% of the fuel sources used to generate steam and hot air are fossil fuels and non-renewable natural resources. Nevertheless, the thermal plant that heats the hot oil (E.P.A) is exclusively dependent on burning natural gas.

**FIGURE 3** Thermal Energy balance for 1.0 m³ of MDF.**FIGURA 3** Balanço de Energia Térmica para 1,0 m³ do MDF.

The interest in reducing fossil fuels in order to reduce global warming, coupled with the increase in fuel prices and electricity, makes the energy issue a focal

point of importance in the coming years to mills that seek to maintain the competitiveness reducing their costs and their dependence on fossil fuels (WILSON, 2010).

Emissions analysis

On-site outputs for MDF production involve a small quantity of emission to the land (wood waste and boiler fly ash to agricultural use), and air emissions (see Table 4).

Carbon Dioxide involves the highest emission contribution in MDF production. In detail, the CO_2 (fossil) comprises 76.9% of total emissions ($34.7 \text{ kg}\cdot\text{m}^{-3}$). In this study, it was tracked the CO_2 for fossil-fuel sources. The CO_2 from combustion of biogenic sources is not considered a greenhouse gas (GHG) for the reason that its carbon life cycle is a closed loop in that the CO_2 (biogenic) is reabsorbed by the growing of trees, liberating oxygen to the atmosphere and consuming the carbon to make more wood (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY - USEPA, 2003; WILSON, 2010). Therefore, the CO_2 emissions from combustion of wood fuels were not reported in the survey.

The CO_2 is emitted from three elementary processes (Figure 4). The processes are: i) Alimentations - CO_2 derived from the combustion of diesel fuel; ii) Drying (E.P. B) - CO_2 derived from the combustion of natural gas in the Energy Plant B (E.P. B). The CO_2 generated is conducted by hot air used in the dryer; iii) Thermal plant - CO_2 derived from the combustion of natural gas used in E.P. A for heating the hot oil.

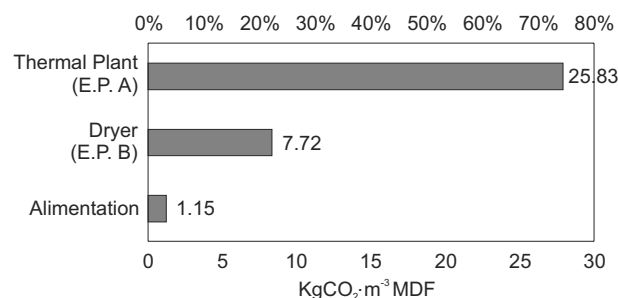


FIGURE 4 CO_2 fossil contribution per elementary processes.
FIGURA 4 Contribuição do CO_2 fóssil por processos elementares.

The combustion of natural gas in E.P. A has the largest impacts on the fossil CO_2 emissions (with a contribution of 74.5%). The use of natural gas in E.P. B characterizes 22.2% and the burning of diesel in alimentation represents 3.3% of CO_2 emissions.

About other compounds, the carbon monoxide (CO) is the second largest contributor (10%) to

emissions, generated in the E.P. B. NO_x (2.8%) and VOCs (2.5%) are generated in the following processes: alimentation, drying and thermal plant. CH_4 , N_2O , and Pb are generated in reason of the combustion of diesel oil.

The particulate emission that occur in the deliberator, drying, pressing, sawing and sanding process, represents 1.3% ($0.6 \text{ kg}\cdot\text{m}^{-3}$) of total air emissions. The formaldehyde (H_2CO) emissions are related to the use of UFR. Moreover, the type and amount of resin used, the scavenger use, the pressing time, and the thickness of the panel, guarantees the physical-mechanical properties of MDF and at the same time, its influence on the quantity of formaldehyde (H_2CO) emitted. The other emissions (SO_2 , H_2SO_4 , and SO_x) totaled 0.9% of air emissions on the on-site MDF industry.

Renewable sources dependence

The LCI analysis of the MDF allows verifying the contribution of non-renewable and fossil fuels in the manufacturing system. Figure 5 provides an overview of all the energy sources used to produce 1.0 m^3 of MDF in this study.

The contribution of renewable sources in MDF production represents 80.8% of total sources of energy required to produce 1 m^3 of MDF. The study reported a low dependence of fossil and non-renewable sources (19.2%) when compared with other studies (ATHENA..., 2009; RIVELA et al., 2007; WILSON, 2010). Furthermore, the natural gas used in E.P. A represents 63% of the total non-renewable and fossil sources.

Regarding the use of electricity, Brazilian electric mix was taken into account. Brazilian electricity is considered a clean system based on its unique characteristics, mainly the prevalence of hydropower (RIBEIRO; SILVA, 2010). The use of renewables in Brazilian electricity production is approximately 86.3% (BRASIL, 2011, base year 2010). In this way, electricity contributes 16% of total non-fossil sources and 25% of total renewable sources for MDF manufacturing.

Compared with the literature, the study of Silva et al. (2013) shows that for the production of 1.0 m^3 wood panel MDP (Medium Density Particleboard) in Brazil are consumed 507 MJ electricity. The significant difference is due mainly to the electricity consumption in defibrator process during the MDF production.

Wood fuel is considered global-warming and climate-change neutral (WILSON, 2010). The use of wood as fuel has benefits; it is a sustainable and renewable fuel that is taking the place of fossil fuel. In

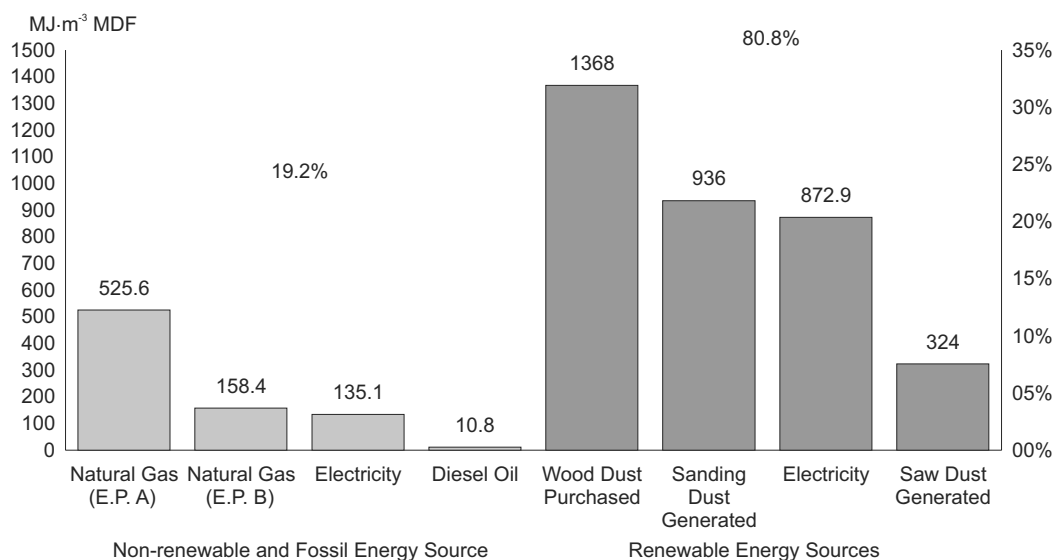


FIGURE 5 Consumption of renewable and non-renewable source in MDF production.

FIGURA 5 Consumos de fontes renováveis não renováveis na produção do MDF.

terms of energy, the industry produces 41.4% of its total consumption. The energy comes from wood fuel generated in the process (renewable energy source). The MDF industry purchased approximately 45.3% of its demand, while 54.7% were generated in the boundaries of the system being studied.

Furthermore, we recommend increasing the part of renewable energy used in thermal plants, upon availability, more wood fuels. These modifications would allow reducing the use of non-renewable and fossils sources and decreasing emission levels for CO₂ fossils, for example.

CONCLUSIONS

This study presented a LCI for the production of 1.0 m³ of MDF manufacturing in the Brazilian industry (on-site system boundary). Special attention was paid to the inventory analysis in terms of energy, emissions, and renewable sources dependence. Although this study reports the technological state-of-art of MDF production system in Brazil, it is noteworthy that due to specific conditions of this case (specific consumptions, Brazilian electricity matrix, modal systems and raw materials) the results are restricted to industry-specific conditions of this study.

In order to produce 1.0 m³ of MDF was required 4320 MJ (76.6% thermal and 23.4% electric energy, for the specific conditions of the industry surveyed). Recycled wood fuel in the industry represents 41.4% of its total energy consumption. 52.8% of thermal energy is required

for the drying process of wood fiber. About emissions, CO₂ is a major emission during the MDF production system. Natural Gas contributes with 96.7% of total CO₂ fossil. CO₂ emission from the energy plant B (E.P. B) can be saved using more wood fuels instead of natural gas.

The results can be used for strategic decisions for improving the environmental performance of MDF. For example, changing the E.P. B for a thermal plant that uses wood residues as fuel can decrease the level of dependence of non-renewable sources (from approximately 19.2% to 7.1%) and reduce the CO₂ fossil emissions.

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