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“Understanding wood modification through an integrated scientific and environmental impact approach”
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Energy and environmental profile comparison of TMT production from two different companies - a Spanish/Portuguese case study

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Life Cycle Assessment (LCA) is a technique for assessing the environmental aspects and potential impacts associated with a product and has been increasingly used to identify processes or stages in the wood chain with a high environmental impact or to highlight areas where environmental information is unknown. The main aim of this study was to quantify and compare the environmental impacts and the energy used for the production of one cubic meter of Thermally Modified Timber (TMT) by two different companies, one in Spain and the other in Portugal, using the LCA methodology. The LCA study was developed based on ISO 14040/44 standards. The inventory analysis and, subsequently, the impact analysis were performed using the LCA software SimaPro8.1.0.60. The method chosen for the environmental impact assessment was ReCiPe, and for energy use the Cumulative Energy Demand method was chosen. The results show that to produce 1 m^3 of thermally modified pine timber the Portuguese company used 14.38 GJ of cumulative energy demand, of which 1.92 GJ was nonrenewable and 12.46 GJ renewable, and the Spanish company used a total of 17.55 GJ, of which 2.52 GJ was nonrenewable and 15.03 GJ renewable. The thermally modified pine timber produced by the Spanish company presented the best environmental results for 13 impact categories in comparison to the 5 best environmental results presented by the Portuguese company. From the weighting triangle, we can conclude that the Portuguese pine boards have a lower environmental impact than Spanish pine boards if a high weight (> 40%) is given to resources, while a weight of <80% is given to human health; otherwise the opposite is true. Regardless of the company, the energy used in the thermal treatment process was identified as the main factor responsible for climate change, acidification, eutrophication, photochemical oxidant formation, metal depletion and fossil depletion. This has to be expected as the treatment is based on heat production and no chemicals are added during the heat treatment process. The round wood production was identified as the leading process responsible for ozone depletion and also presented remarkable contributions to eutrophication and photochemical oxidant formation.

Keywords: Energy, Life Cycle Assessment, Thermally Treated Timber

Introduction

Wood is a natural renewable material that grows in abundance in Portugal where maritime pine (*Pinus pinaster* Aiton.) is the forest species with the most planted area, reaching 710 × 10^3 ha in 2013 and representing 23% of the total forest area (DNGF 2013). According to EN-350-2 (1994), pine heartwood is considered to be in durability class 4 (low durability). However, the wood durability can be increased through the application of wood-preservative systems or by wood modification. Heat treatment is one of the most successful wood modification processes, allowing for wood durability to be improved by three or four times (Marra et al. 2015) to durability class 1 or 2. Heat-treatment has been known for a very long time but it is only in the last decade that several different methods were developed, most of them in Europe (Esteves & Pereira 2009, Sandberg & Kutnar 2015). ThermoWood (2003) process is a technologically advanced process involving the use of heat and steam. The wood is heated to temperatures from 160 to 230 °C, thus changing its molecular structure, making it more dimensionally stable and resistant to biodegradation, turning it into wood with properties similar to tropical species. The heat-treatment usually varies from medium

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to high intensity. Thermo D (intense treatment) is conducted at a higher temperature. The resulting products have high dimensional stability and durability, significantly increasing wood life service. This intense treatment ensures wood can be used both indoors and outdoors. It is commonly used for lining walls and cladding (indoors and outdoors), indoor floors and decking. Thermo S (soft treatment) is a medium-temperature treatment that increases the stability of wood, giving it a bright medium brown (honey) tone. The soft treatment is recommended exclusively for indoor use such as floors, linings and other decors. The production process of thermo-modified wood has no chemical compounds at all, thereby avoiding harmful effects to the environment and preserving the natural beauty of wood. An extensive review of the research concerning properties of thermally-treated wood can be found in Esteves & Pereira (2009), and the relationship between wood modification and the associated environmental impacts in Sandberg & Kutnar (2015).

In general, for all companies, and particularly for wood companies, the environmental performance of products has become a growing concern, due to the increasing restrictive legislation and more consumer awareness of environmental issues. Life Cycle Assessment is a technique for assessing the environmental aspects and potential impacts associated with a product (ISO 2006a), and it has been increasingly used to improve wood production as well as to identify processes or stages in the wood chain with a high environmental impact or highlight areas where environmental information is unknown (González-García et al. 2009, Ferreira & Domingos 2012, 2014, Sandberg & Kutnar 2015).

LCA has already been used to study thermally modified timber products (ThermoWood 2008, Ferreira et al. 2014a, Marra et al. 2015), as well as forest-based products (Werner et al. 2007, González-García et al. 2014, Ferreira et al. 2014b). Recently, state of the art LCA was conducted in the forestry sector by Klein et al. (2015) with a special focus on Global Warming Potential (GWP). However, LCA studies are still lacking for the forest sector. In order to allow better comparability between LCA studies, those authors proposed some methodical approaches regarding the harmonization of system boundaries, functional units, considered processes, and impacts allocation. To identify the environmental impacts related to ThermoVacuum treated timber used for cladding and to compare it against alternative products (untreated cladding and preservative treated cladding), Marra et al. (2015) concluded that the use of thermally treated timber had the lower ecosystem damage, which is the most important category, and ThermoVacuum cladding damage categories were lower than preservative treated cladding.

According to Sandberg & Kutnar (2015) and ThermoWood (2008), thermally treated wood products can contribute to mitigating climate change and promoting sustainable development by reducing energy consumption, pollution and emissions while increasing wood performance. In this study, we aim to quantify and compare the energy use and the environmental impacts of thermally modified maritime pine boards production in a Portuguese and in a Spanish company using the LCA methodology.

Materials and methods

The LCA study of thermally modified maritime pine boards was performed based on ISO-14040 (ISO 2006a) and ISO-14044 (ISO 2006b) standards.

Goal and scope of the study

The aim of this study was to assess and compare the potential life cycle environmental impacts associated with the production of thermally modified maritime pine boards by a Portuguese and a Spanish company. Company decision makers will be informed of the LCA study (cradle-to-gate) results in order to discover which processes provide better opportunities to improve the environmental impacts of production.

Functional unit

The functional unit was defined as 1 m^3 of thermally modified maritime pine boards. The choice of this functional unit is in agreement with other thermally modified product systems also assessed from an LCA perspective (Werner et al. 2007, Klein et al. 2015, Marra et al. 2015).

System boundary

The system boundary for the product system in this study is represented in a simplified way in Fig. 1. The modules included inside the boundaries are raw material extraction and processing, processing of secondary material input (*e.g.*, recycling processes), transport to the manufacturer, heat production and manufacturing. The Portuguese company uses gas (propane) plus wood residues for heat production and the Spanish company uses only natural gas.

Allocation procedure

The forest process delivers pine round wood as a product and industrial and residual wood as co-products. The sawing and planing process of the product system delivers the product, pine boards, and the following co-products: bark, sawdust and chips that can be used as raw materials for other product systems (*i.e.*, particle board,

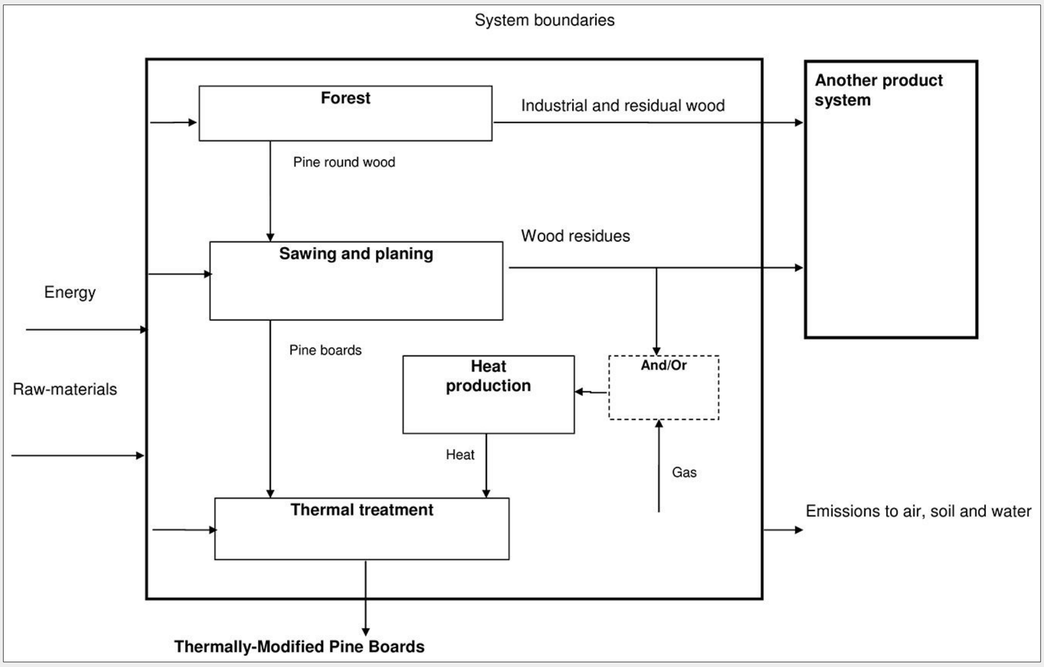

Fig. 1 - Product system boundary.

energy etc.). In order to solve this allocation problem, the environmental burdens are allocated to both product and co-products based on their economic value. This is in agreement with other forest-related LCA studies (Werner et al. 2007). According to these authors, as the economic allocation cannot respect the mass and energy balance of the products, correcting modules are defined in order to add or subtract the CO_2 uptake. Inputs that can be clearly attributed to specific products (*e.g.*, gas is used only in thermal treatment) are allocated exclusively to them.

As the allocation approach can have a strong effect on the results, a sensitivity analysis was also proposed considering both volume and economic allocations between the product and co-products in order to identify differences in the environmental profiles.

Tab. 1 - Dataset for production of 1 m^3 of Portuguese thermally treated maritime pine boards.

Process	Inputs	Value	Outputs	Value
Forest	-	-	Pine round wood	2.09 m^3
Sawing and planning	Round wood (maritime pine)	2.09 m^3	Wood boards	1.09 m^3
	Electricity	21.8 KWh	Wood residues (out)	0.592 m^3
	Round wood transport	52 t Km	Wood residues (inside heat production)	0.408 m^3
Thermal treatment	Wood boards	1.09 m^3	Thermally modified pine boards	1 m^3
	Electricity	72.33 KWh	Water	0.109 m^3 (steam)
	Heat from gas (propane)	925 MJ (19.97 Kg)	-	-
	Heat from wood residues	3454 MJ (0.408 m^3)	-	-
	Water	0. 109 m^3	-	-

Tab. 2 - Dataset for production of 1 m^3 of Spanish thermally treated maritime pine boards.

Process	Inputs	Value	Outputs	Value
Forest	-	-	Pine round wood	1.86 m^3
Sawing and planning	Round wood (maritime pine)	1.86 m^3	Wood boards	1.09 m^3
	Electricity	28.28 KWh	Wood residues (out)	0.77 m^3
	Round pine wood transport	35 t Km	-	-
Thermal treatment	Wood boards	1.09 m^3	Thermally modified pine boards	1 m^3
	Rope	0.02 Kg	Water	0.004 m^3
	Electricity	24 KWh	Rope	0.02 Kg
	Heat from natural gas	1465 MJ	-	-
	Wood boards transport	22 t Km	-	-
	Water	0.004 m^3	-	-

Inventory analysis

The inventory analysis and subsequent impact analysis were performed using the LCA software SimaPro 8.1.0.60 (PRé 2015) and associated databases and methods.

Data type/data collection

The datasets for the products and processes included in the system boundaries are company data and are presented in Tab. 1 and Tab. 2 for the Portuguese and Spanish case studies, respectively. The thermo-treatment used is Thermo D (intense treatment) to reach a durability level which complies with the requirements for durability class 3.2, according to EN-335-1 (2006) standard, and for use in construction of exterior decks or cladding. The data is related to 2014 and all the wood comes from forests in the region where the facilities are located. All the materials and energy used for the production of the functional unit were accounted for.

The Portuguese case study was based on maritime pine boards with length = 0.6-2.6 m, width = 100-120 mm and thickness = 26 mm. The average moisture content and density of wood vary from the moisture content (u>70%) and density (d=1000 kg m^{-3}) of "green wood" to that (u=12% and d=565 Kg m^{-3}) of "dry wood." The electricity consumed in the production processes is delivered by Energies of Portugal (EDP) as "EDP Comercial Empresas" mix (29% hydro, 10% wind, 4.2% renewable cogeneration, 1.7% other renewable, 0.3% urban solid wastes, 10.7% cogeneration fossil, 4.7% natural gas, 29% coal, 9.6% nuclear and 0.3% fuel oil), which is different from the Portuguese average mix (ERSE 2016).

The Spanish case study was based on flat boards of maritime pine with the following dimensions: thickness = 21 mm, width = 90 mm and length = 2400 mm. The total of 220 wood boards have a volume of 1 m^3. The average moisture content and density of wood varies from the moisture content (u>70%) and density (d=1250 kg m^{-3}) of "green wood" to that (u=11% and d=590 Kg m^{-3}) of "dry wood". Regarding power sources used for electricity consumption, the ENDESA mix (26.5% renewables: pure + hybrid, 0.1% high efficiency cogeneration, 10.3% cogeneration, 12.9% natural gas combined cycles, 20% coal, 2.9% fuel/gas, 25.3% nuclear and 2% others) was used because ENDESA provided electricity to the factory, and this electricity mix is different from the Spanish average mix (CNMC 2016).

As the thermal treatment includes kiln drying of wet wood (u=70%) down to u= 12%, a shrinkage of 9% (in volume) was considered as in Werner et al. (2007). Air emissions released from the wood are not accounted for because they were considered to be the same emissions that would occur if the wood was used without treatment.

The following assumptions were made for the datasets:

- The infrastructure of thermo-modified pine board production facilities was not taken into account as it has been assumed that its contribution to the overall impact is negligible (Jungmeier et al. 2002).
- The inventory datasets for the background system (such as electricity) were obtained and adapted as necessary from databases presented in SimaPro 8.1.0.60 software and other sources as presented in Tab. 3. Whenever possible, the Ecoinvent unit process V2.2 was used, otherwise another database was chosen to model the system, as in the processes "heat from Liquefied Petroleum Gas (LPG)" and "natural gas" for which the Franklin USA 98 database was used.

Life cycle impact assessment (LCIA)

The method chosen for the environmental impact assessment was ReCiPe Midpoint and Endpoint (H) ver. 1.12 / Europe ReCIPE H/A, and for energy use, the Cumulative Energy Demand ver. 1.09 (PRé 2015) was chosen.

At the midpoint level, 18 impact categories are addressed in ReCiPe: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionizing radiation (IR),

Tab. 3 - Dataset for the background system.

Study	Process	Equivalent process	Source
Portuguese case study	Round wood	Round wood, softwood, under bark, u=70% at forest road/RER U	Ecoinvent database v. 2.2 (adapted according Ferreira & Domingos 2012)
	Electricity	Electricity, low voltage, at grid/EDP 2014 U	Ecoinvent database v. 2.2 (adapted according to electricity source of EDP 2014)
	Heat from gas (propane)	Heat from LPG FAL	Franklin USA 98 database
	Heat from wood residues	Wood chips, from industry, softwood, burned in furnace 300KW/CH U	Ecoinvent database v. 2.2 (adapted to the study)
Spanish case study	Round wood	Round wood, softwood, under bark, u=70% at forest road/RER U	Ecoinvent database v. 2.2
	Electricity	Electricity, low voltage, at grid/ENDESA 2014 U	Ecoinvent database v. 2.2 (adapted according to electricity source of ENDESA 2014)
	Rope	Yarn, jute (GLO), market for Conseq	Ecoinvent 3
	Heat from natural gas	Heat from nat. gas FAL	Franklin USA 98 database
Common	Transport of round wood or wood boards	Transport, lorry >16 ton, fleet average/RER U	Ecoinvent database v. 2.2

agricultural land occupation (ALO), urban land occupation ULO), natural land transformation (NLT), water depletion (WD), metal depletion (MD) and fossil depletion (FD). At the endpoint level, most of these midpoint impact categories are multiplied by damage factors and aggregated into three endpoint categories: (i) Human health; (ii) Ecosystems; and (iii) Resources. The three endpoint categories are normalized and the weighting triangle is graphically built showing the outcome of the comparisons between any two items for all possible weighting sets (Hofstetter et al. 2000).

In the Cumulative Energy Demand method, energy resources are divided into five impact categories: (i) nonrenewable, fossil; (ii) nonrenewable, nuclear; (iii) renewable, biomass; (iv) renewable, wind, solar and geothermal; and (v) renewable, water.

Results and discussion

The results show that to produce 1 m^3 of thermally modified pine timber the Portuguese company used 14.38 GJ of cumulative energy demand of which 1.92 GJ was nonrenewable and 12.46 GJ renewable, and the Spanish company used a total of 17.55 GJ of which 2.52 GJ was nonrenewable and 15.03 GJ renewable (Tab. 3).

Tab. 4 shows the contributions to the impact categories considered in the ReCiPe Midpoint method for 1 m^3 of thermally modified pine boards production by the Portuguese and Spanish companies, and Fig. 2 shows the comparative environmental profiles. The contributions of Portuguese and Spanish treated boards to climate change, particulate matter formation and agricultural land occupation are almost equal. The Spanish treated boards are better (<50%) than Portuguese for ozone depletion, marine eutrophication, water depletion and metal depletion and much better (>50%) for freshwater eutrophication, toxicity (HT, TE, FE and MET), urban land occupation and natural land transformation. The Portuguese treated boards are better than Spanish for photochemical oxidant formation, ionizing radiation and fossil depletion and much better for terrestrial acidification.

Related to the processes included in the Portuguese product system boundary, the electricity process is the main one responsible for freshwater eutrophication (70%), freshwater ecotoxicity (58%), marine ecotoxicity (55%), ionizing radiation (76%), water depletion (77%) and metal depletion (57%). Heat production from LPG used in the thermal treatment process is the main process responsible for climate change (48%) and fossil depletion (53%). Wood residues burned in the furnace to produce heat, for that process is the main factor responsible for human toxicity (41%), photochemical oxidant formation (35%) and particulate matter formation (59%). Round wood production at the forest road is the main process responsible for ozone depletion (47%), terrestrial ecotoxicity (58%), land occupation (agricultural 93% and urban 92%) and natural land transformation (92%). The contribution of the transport process to the environmental profile is almost negligible (varies from 0 to 3.5%) for most of the impact categories, except for ozone depletion (13%).

Related to the processes included in the Spanish product system boundaries, the electricity process is the main one responsible for human toxicity (71%), ecotoxicity (freshwater 73% and marine 71%), ionizing radiation (89%), water depletion (70%) and metal depletion (54%). Heat production

Tab. 4 - Impact assessment results associated with the production of 1 m^3 of thermally modified pine boards under different company practices. (CC): climate change; (OD): ozone depletion; (TA): terrestrial acidification; (FE): freshwater eutrophication; (ME): marine eutrophication; (HT): human toxicity; (POF): photochemical oxidant formation; (PMF): particulate matter formation; (TET): terrestrial ecotoxicity; (FET): freshwater ecotoxicity; (MET): marine ecotoxicity; (IR): ionizing radiation; (ALO): agricultural land occupation; (ULO): urban land occupation; (NLT): natural land transformation; (WD): water depletion; (MD): metal depletion; (FD): fossil depletion.

Impact category	Unit	Portuguese thermally treated boards (1 m^3)	Spanish thermally treated boards (1 m^3)
CC	kg CO_2 eq	1.33E+02	1.31E+02
OD	kg CFC-11 eq	5.48E-06	4.77E-06
TA	kg SO_2 eq	7.92E-01	1.71E+00
FE	kg P eq	3.16E-02	9.54E-03
ME	kg N eq	4.44E-02	3.24E-02
HT	kg 1.4-DB eq	6.64E+01	1.24E+01
POF	kg NMVOC	1.21E+00	1.39E+00
PMF	kg PM10 eq	4.45E-01	4.52E-01
TET	kg 1.4-DB eq	2.86E-02	6.89E-03
FET	kg 1.4-DB eq	7.13E-01	2.34E-01
MET	kg 1.4-DB eq	7.51E-01	2.45E-01
IR	kBq U235 eq	1.63E+01	1.94E+01
ALO	m^2 a	1.80E+03	1.90E+03
ULO	m^2 a	4.24E+01	1.92E+01
NLT	m^2	9.50E-01	1.74E-01
WD	m^3	1.58E+00	1.05E+00
MD	kg Fe eq	4.08E+00	2.27E+00
FD	kg oil eq	4.08E+01	5.43E+01

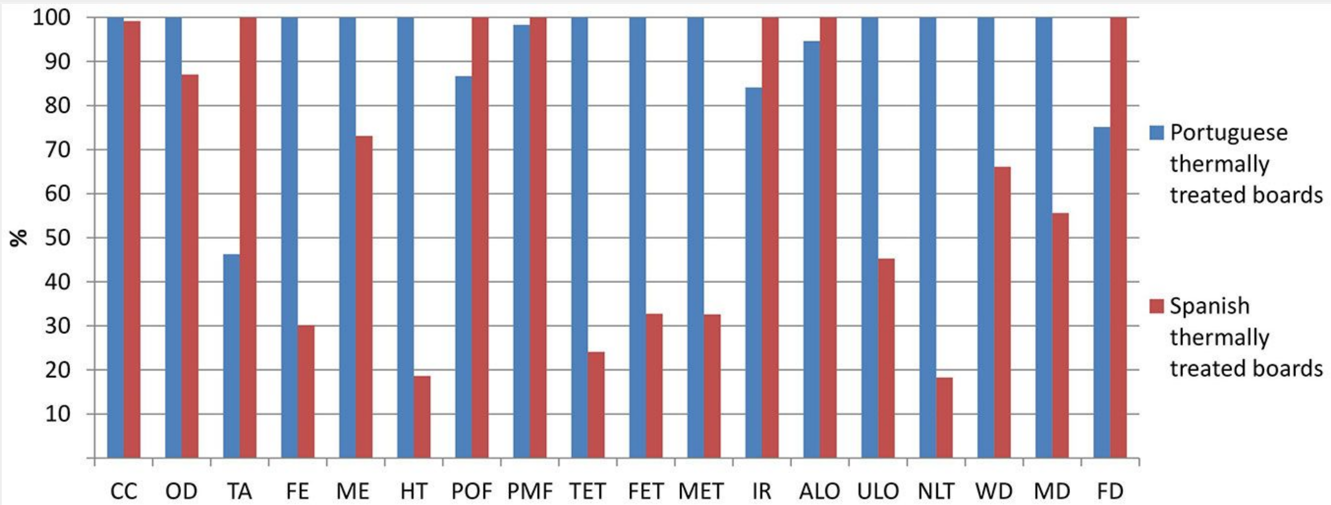

Fig. 2 - Comparative profiles of the thermally modified pine boards by company. (CC): climate change; (OD): ozone depletion; (TA): terrestrial acidification; (FE): freshwater eutrophication; (ME): marine eutrophication; (HT): human toxicity; (POF): photochemical oxidant formation; (PMF): particulate matter formation; (TET): terrestrial ecotoxicity; (FET): freshwater ecotoxicity; (MET): marine ecotoxicity; (IR): ionizing radiation; (ALO): agricultural land occupation; (ULO): urban land occupation; (NLT): natural land transformation; (WD): water depletion; (MD): metal depletion; (FD): fossil depletion.

from natural gas is the main process responsible for climate change (67%), terrestrial acidification (82%), photochemical oxidant formation (51%), particulate matter formation (69%) and fossil depletion (74%). Round wood production at the forest road is the main process responsible for ozone depletion (55%), marine eutrophication (48%), terrestrial ecotoxicity (76%), land occupation (agricultural almost 100% and urban 99%) and natural land transformation (97%). The contribution of the transport process for the environmental profile is small (varies from 0 to 10%) for most indicators, except for ozone depletion (22%) and metal depletion (15%).

Technical wood drying infrastructure, tap water and yarn jute for packaging pine boards were confirmed to contribute less than 1% for all the impact categories.

Although it was not the purpose of this study to prepare an environmental product declaration according to EN-15804 (2013) for related impact categories considered in the PCR-2012:01V2.01 (2016) recommendations, the following comments can be addressed.

Terrestrial acidification (TA)

The main source of this indicator is energy production with approximately 84% for Portuguese treated boards (35% is due to heat from wood residues and 33% from electricity) and almost 90% for Spanish treated boards (82% is due to heat from natural gas).

Freshwater eutrophication

Freshwater eutrophication is mainly due to electricity production for Portuguese and Spanish treated boards representing 70% and 80%, respectively. Another important source is fossil fuel burned in harvesting pine round wood representing almost 27% and 14% of this indicator for Portuguese and Spanish boards, respectively.

Global warming (climate change)

Approximately 86% and 81% of this indicator is due to energy production for Portuguese and Spanish treated boards, respectively. Included in that value, heat from gas is responsible for 48% and 67%, respectively.

Photochemical oxidant formation

As for the above indicators, the main source for this indicator is energy production for both Portuguese and Spanish treated boards with 68% and 57%, respectively. However, another 28% and 39% applies to fossil fuel burned in harvesting pine round wood in Portuguese and Spanish treated boards, respectively.

Ozone layer depletion (ODP)

Fossil fuel burned in harvesting pine round wood is still the process that most contributes to this indicator with 47% and 55% for Portuguese and Spanish treated boards, respectively. Electricity and transport are other processes with a significant contribution: 29% and 13% for Portuguese and approximately 22% each for Spanish treated boards, respectively.

Fossil depletion

Heat from gas is the main source for this indicator with 53% for Portuguese treated boards and 74% for Spanish treated boards. Electricity production with 25% and fossil fuel burned in harvesting pine round wood with 12% are other sources that contribute significantly to this indicator for Portuguese treated boards.

In Europe, the characterization factors outlined in EN-15804 (CML-IA method) shall be used. The ReCiPe Midpoint method, used in this study, integrates the "problem oriented approach" of CML-IA that defines the impact categories at a midpoint level. Therefore, the previous comments make sense.

Comparing the results of this study with others in the literature is limited by the restrictions of the data and the use of different methodological approaches in the reports. Nonetheless, some comparisons can be made. Tab. 5 presents a comparison of the results of this study (cradle-to-gate) with those reported in Marra et al. (2015), where a cradle-to-grave life cycle assessment was performed using the same impact assessment method (ReCiPe Endpoint/Europe H/A/Normalization) to identify the environmental impacts related to ThermoVacuum treated timber used for

Tab. 5 - Comparison of Portuguese and Spanish thermally threated boards with Thermo-Vacuum cladding. (‡) Source: Marra et al. (2015); (EU eq): European equivalents.

Impact category	Unit	Portuguese thermally treated boards (1 m^3)	Spanish thermally treated boards (1 m^3)	Thermo-Vacuum cladding (‡) (1 m^3)
Human Health	EU eq.	0.0172	0.0154	0.035
Ecosystems	EU eq.	0.1403	0.1362	0.26
Resources	EU eq.	0.0228	0.0296	0.06

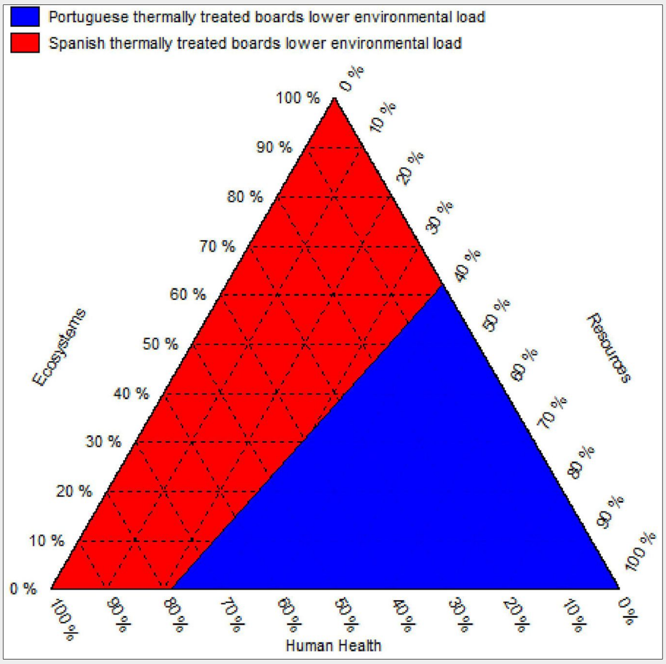

Fig. 3 - Weighting triangle showing the line of indifference and sub-areas with their specific ranking orders.

cladding. As the versions (1.12 and 1.13) of the method used and the life cycle stages were different, we can only conclude that for all functional units, Ecosystems is the most important damage category followed by Resources and Human Health. The highest damage category values for Thermo-Vacuum treated timber are partially explained by the additional life cycle stages ("use" and "end-of-life") considered in that study.

The weighting triangle

For the impact assessment method ReCiPe Endpoint that uses three damage categories, as described above, SimaPro has an option to automatically generate a triangle during the normalization step. The triangle graphically shows the outcome of the comparison between any two items for all possible weighting sets. Each point within the triangle represents a combination of weights that add up to 100%.

The line of indifference in the weighting triangle and the sub areas with their specific ranking orders is presented in Fig. 3. The line represents weighting factors for which Portuguese and Spanish treated pine boards have the same environmental loads. From the weighting triangle we can conclude that the Portuguese boards have a lower environmental impact than Spanish boards if a high weight (>40%) is given to Resources, while a weight of <80% is given to Human Health. Otherwise the opposite is true.

Sensitivity analysis

As reported before, the allocation approach can have a strong effect on the results. In order to identify differences in the environmental profiles, a sensitivity analysis was done to determine the effects of different assumptions on LCA results, based on using volume or economic allocations between the product and co-products. Factor allocations for the products and co-products studied are presented in Tab. 6. If we consider mass allocation instead economic allocation, the environmental profiles of Portuguese and Spanish thermally treated boards are better. For Portuguese treated boards, the indicators reduce to between 2% for human toxicity to 20% for land occupation and transformation. For Spanish treated boards the indicators reduce to between 4% for terrestrial acidification to 29% for land occupation and transformation. In this case, Spanish treated boards are now better than Portuguese for 14 (instead of 12) impact categories of the 18 considered in this method. PMF changed from -2% to +1% and ALO changed from -5% to +6% related to economic allocation.

Considering the use of electricity from the Portuguese grid (instead of EDP) and from the Spanish grid (instead of ENDESA) the results show that Spanish treated boards are now better than Portuguese for 13 (instead of 12) impact categories. PMF changed from -2% to +1% related economic allocation.

Tab. 6 - Allocation procedure.

Allocation Factors	Portuguese thermally treated boards (1 m^3)		Spanish thermally treated boards (1 m^3)	
	Economic allocation	Mass allocation	Economic allocation	Mass allocation
Wood boards	0.64	0.5	0.79	0.56
Wood residues	0.36	0.5	0.21	0.44

Conclusion

Our results showed that 1 m^3 of Spanish thermally treated pine boards are more energy intensive (17.55 GJ m^{-3}) than Portuguese (14.38 GJ m^{-3}). Spanish treated boards present the best environmental results for 12 impact categories, while Portuguese only presented the best environmental results in 6 impact categories.

For both product system boundaries, the electricity process is the main process responsible for ecotoxicity (freshwater and marine), ionizing radiation and depletion (water and metal) and for freshwater eutrophication. Heat production from gas used in thermal treatment process is the main factor responsible for climate change and fossil depletion. This process is also the main one responsible for terrestrial acidification (82%), photochemical oxidant formation (51%) and particulate matter formation (69%) for the Spanish functional unit. Fossil fuel burned in harvesting round wood is the main factor responsible for ozone depletion, terrestrial ecotoxicity, land occupation (agricultural and urban) and natural land transformation. Moreover, this process is the main one responsible for marine eutrophication (48%) for the Spanish functional unit. The contribution of transport processes to the environmental profiles is almost negligible for the Portuguese product (varies from 0 to 3.5%) for most impact categories except for ozone depletion (13%) and is non-significant for the Spanish product (varies from 0 to 10%) for most indicators, except for ozone depletion (22%) and metal depletion (15%). Wood residues burned in the furnace to produce heat for Portuguese treated boards is the main factor responsible for human toxicity (41%), photochemical oxidant formation (35%) and particulate matter formation (59%).

The environmental indicators for both Portuguese and Spanish treated boards are better if mass allocation is used instead of economic allocation.

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