Journal of Cleaner Production xxx (2015) 1–15

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

The environmental footprint of interior wood doors in non-residential buildings – part 1: life cycle assessment

Aline Cobut*, Pierre Blanchet, Robert Beauregard

Renewable Materials Research Center, Faculté de foresterie, de géographie et de géomatique, Université Laval, Québec, QC, G1V 0A6, Canada

A R T I C L E I N F O

Article history:
Received 17 August 2013
Received in revised form
23 March 2015
Accepted 21 April 2015
Available online xxx

Keywords:
Interior wooden doors
LCA
Ecodesign
Non-residential buildings
Appearance wood products

A B S T R A C T

Integrating environmental aspects into industrial practices has become a necessity. In fact, climate change and resource depletion have been established scientifically and can no more be neglected. Life Cycle Assessment is acknowledged to be an efficient tool to establish a product environmental profile and can be useful to businesses wishing to analyze their environmental record. Decreasing a building environmental footprint implies, among other considerations, a proper choice of building materials, both structural and architectural. A good avenue would be to select low environmental impact materials from *cradle-to-grave*. Architectural wooden doors are often specified in non-residential buildings in North America. However, only one Life Cycle Assessment has been carried out on wooden doors. This study explores the *cradle-to-grave* environmental profile of an interior wood door in a North American context. According to the results, the main contributor to the product impacts is the production of raw materials, especially the particleboard component, and their transportation to the manufacturing plant. The urea formaldehyde production is the main reason for particleboard impacts among the three damage categories, human health, climate change and resources, of *IMPACT 2002+*. The other life cycle stages that have a noticeable influence on the door environmental impacts are shipping and end-of-life. Transportation as a whole affected the system total environmental score. The current results could serve as a basis for ecodesign implementation.

1. Introduction

1.1. Building ecological footprint

The building sector has a large environmental impact when looking at carbon dioxide emissions, energy consumption and material extraction. According to Bribián et al. (2011) building construction and civil works use 60% of the raw material extracted from the lithosphere and the building sector represents 24% of these global extractions. Moreover, Esin (2007) argues that the impact incurred during the production process of building materials has an important role because of building materials life cycle. Furthermore, among all the main carbon dioxide emitting activities, the building sector is one where practical improvement may have significant environment impact reduction, with minimum change in the western world lifestyle (Barker et al., 2007; Levine et al., 2007). This highlights the need for environmentally friendly materials in the building sector.

1.2. Non-residential utilization of appearance wood products in Quebec

The government of the Province of Quebec, Canada, expressed in 2008, the intention to promote the use of wood in non-residential buildings (Béchard, 2008). In buildings, wood utilization is usually related to structural materials and systems. However, a broad range of wood building materials is employed during finishing processes, wood floor covering, wall paneling, ceiling tile, siding, decorative wall paneling, moulding can be listed. Those products have an aesthetical function and they are often used in large volumes. They also show high added value and represent an application of choice for wood products.

A study have been published on the development of wood use in non-residential constructions among building professionals in the province of Quebec, Canada (Drouin et al., 2012). From this research, it has been possible to identify the most specified

* Corresponding author. Tel.: +1 418 656 2438x2131; fax: +1 418 656 2091.
E-mail addresses: aline.cobut.1@ulaval.ca (A. Cobut), Pierre.blanchet@sbf.ulaval.ca (P. Blanchet), robert.beauregard@sbf.ulaval.ca (R. Beauregard).

http://dx.doi.org/10.1016/j.jclepro.2015.04.079

appearance wood products during building design. Wooden doors appear to be at the top of architects' specification in most recent buildings with a 66% rate. The least specified appearance wood products would be wooden windows with 23% of recent non-residential constructions. The study shows also that wooden doors are also more likely than other appearance wood products to be specified in the Canadian National Building Code (CNBC) class B2 buildings for care and detention (physical and cognitive limitations) and commercial buildings (NBC class E). Finally, it has been demonstrated that the use of appearance wood products, like millwork, cabinetry, floor covering, exterior and interior siding vary in an inversely proportional manner to the built area. On the contrary, products such as windows, doors and stairs are specified independently from the designed building area; the biggest constraint for interior wood products in large construction being the maintenance.

1.3. Environmental studies on wooden doors

As far as doors are concerned, only one scientific paper, about doors life cycle assessment (LCA), has been published. Knight et al. (2005) made a comparative LCA of two types of doors, a steel door and a wooden door. However, they made a partial LCA that only includes the cradle-to-gate impacts. Besides, in their report, O'Connor et al. (2009) analyze also the former paper and express that even with a full cradle-to-gate LCA, the conclusions of the Knight et al. study may not be changed because of the major difference of magnitude in their respective environmental performance for both types of doors. The steel door creates 40 times more waste, causes 27 times more greenhouse gas emission and its raw materials acquisition and manufacture consume 22 times more energy. The results also indicate that more air and water pollution are related to steel doors. Nonetheless, the results of Knight et al. cannot be comparable directly with this study. In fact, the study covers only a cradle-to-gate perspective, while our study is a cradle-to-grave LCA. Moreover, the Life Cycle Impact Assessment methodology used is different.

1.4. Design for environment

Ecodesign, also known as Design for Environment (DfE), can be defined as the integration of environmental concerns into product design. The environmental aspects are given the same status as functionality, durability, costs, time-to-market, aesthetics, ergonomics and quality (Pigosso et al., 2010). Ecodesign can be seen as a strategic design activity established to conceive and develop sustainable solutions, and also, as a proactive management approach that directs product development towards environmental impact reductions throughout its life cycle, without compromising other functionalities. It has been largely adopted over the past few years, as the concept of sustainable development grew.

DfE implementation consists in three consecutive phases. Firstly, a target must be defined and possible alternatives are identified. Secondly, a significant amount of environmental data must be collected, analyzed and interpreted. And finally, results must be translated into tools, which go from simple guidelines and design procedures to more sophisticated software systems (Guidice et al., 2006).

Many tools are available to help throughout the process of environmental profiling. LCA can be cited among them. Using LCA, the environmental profile of a product can be established. It then becomes possible to identify the environmental impacts associated with the entire product life cycle. It is also easy to consider that the comparison between different scenarios could help in designing an environmentally friendly product. This study was conducted following this perspective.

1.5. Research aim and scope

The main objective of this research is to establish the environmental profile by the use of LCA from the cradle to the grave of an interior wooden door used in non-residential buildings. This study aims as well at expanding the current knowledge on environmental impact of appearance wood products. The obtained results should enable to target the main sources of environmental footprint in the product life cycle and establish knowledge for building professionals such as architects, interior designers and engineers.

2. LCA methodology

The current research has been carried out following recommendations of the ISO 14040 series (ISO, 2006a, b) for every step of the analysis. This LCA study has been modeled using the SimaPro 7.3.3 software. This tool was chosen because of its broad acceptance in the international LCA community.

2.1. Product system description

The product under study is an interior wooden door used in non-residential construction. The system is based on a standard product made by a commercial and architectural wooden doors manufacturer from the province of Quebec, in Canada. The door is made of three major sub-assemblies: two faces and a core. The main components of the faces are hardwood veneer and fiberboard. The core is composed of structural composite lumber, hardwood and particleboard. The adhesive used in the assembly of the door components is Polyvinyl Acetate (PVAc). Details of the product can be found in Fig. 1. The main function of this product is to close or separate open areas. Secondary functions could be seen as aesthetic or security (intrusions). The door performance ranges from standard duty up to extra heavy-duty.

2.2. Functional unit

The functional unit is the closure and separation of two rooms with communicating surface of 2.1 by 0.9 m using a standard interior wooden door with a thickness of 4.5 cm. The door is assumed to stay in the building as long as its function is needed. The manufacturer guaranties the doors for life but the faces for 40 years. The service life is then assumed to be 40 years.

2.3. System boundaries

The entire life cycle of the product is included in the system. Meaning that, all the steps are considered from the acquisition of the raw materials to the door's end-of-life. This is a cradle-to-grave LCA. Since the manufacturer includes neither the doorframe nor the fittings (door handle and hinges) for the studied product, it has been decided to exclude them from the system.

2.4. Allocation procedure

For the door production, it has been possible to break down the production process for the studied product so then allocations were no longer needed. On the occurrence of using a co-product from a manufacturing process, it has been decided to refer to the allocation factors obtained from the life cycle inventory (LCI) study or to allocation factors from the *Ecoinvent* database (Swiss Centre for Life Cycle Inventories, 2013). The production process of veneer is a

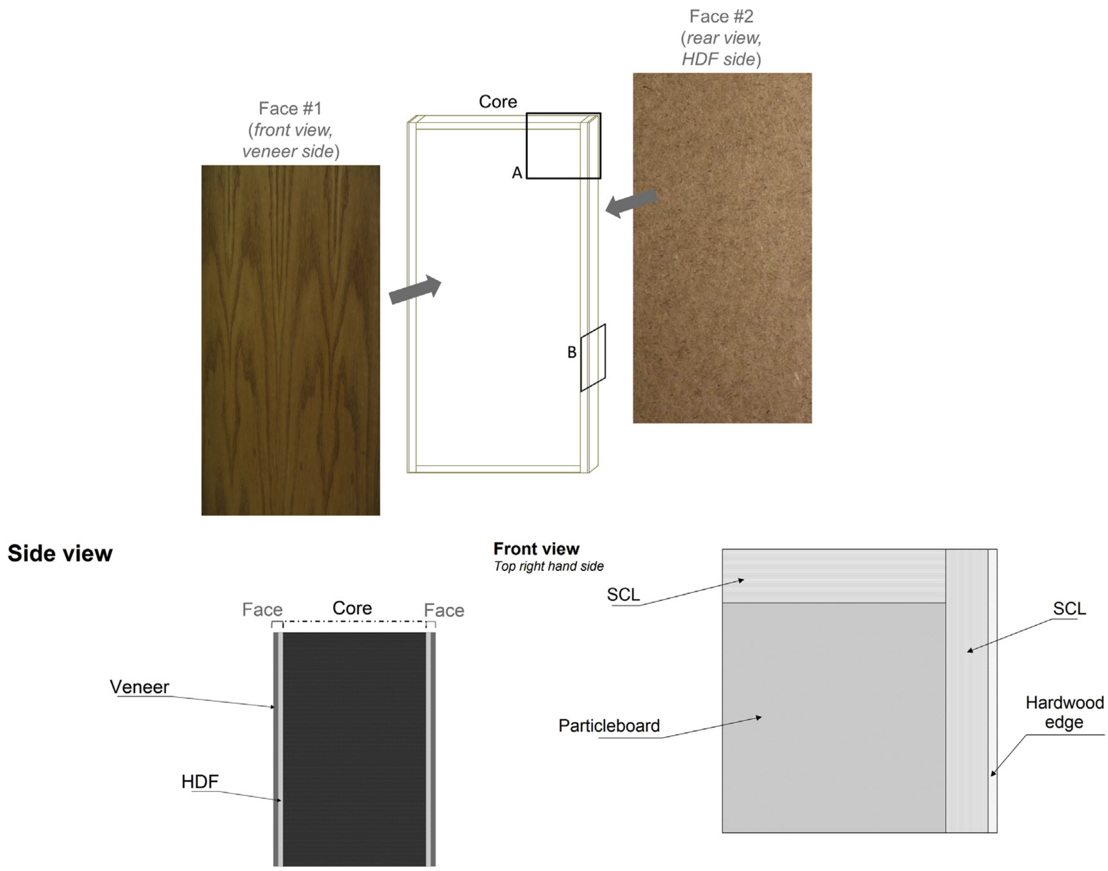

Fig. 1. Detailed representation of the door under study.

multi-output process in which products were given mass allocation factors because mass and value were proportional (Bergman and Bowe, 2011).

2.5. Data sourcing and quality

The primary data, mostly obtained from the manufacturer, were representative of the current technologies and materials used by this company. In the province of Quebec, the market share for commercial and architectural interior wood doors is divided in two major companies, including this manufacturer (25%), that represent 50% and the remaining smaller manufacturers. The data can be considered as representative of the sector. When primary data were not available, the unit processes were selected from the *Ecoinvent* database, the most comprehensive LCI database currently available. Some unit processes, such as electricity grid mix and road transport, have been adapted to a Quebec and North-American context, since *Ecoinvent* is based on European situations that sometimes could not fit all situations.

A sensitivity analysis has been performed on multiple data assumptions to assess the validity of the results. Hence, parameters for transportation have been analyzed such as truck loading for shipping (±25% of actual load, 17.56 tons) and distances for all life cycle stages (±25% of actual distances). The effect of the electricity grid mix for the door production has been tested by considering a US electrical grid mix instead of that of the province of Quebec which is mostly based on hydroelectricity. Allocation rules from *Ecoinvent v2.2* for roundwood have also been analyzed. A decrease of 5% and 10% of allocations to roundwood (hardwood and softwood) has been tested.

2.6. Life cycle inventory (LCI)

The purpose of a LCI is to quantify materials, substances and energy flows that go through the system in accordance with the functional unit and boundaries. An LCI requires a considerable amount of research. Hopefully, LCI databases have been developed and continuously improved worldwide to help in the process. The *Ecoinvent* database, which has been developed by a Swiss initiative in an effort of data centralization, has been selected as a reference in this study (Swiss Centre for Life Cycle Inventories, 2013). In fact, this database is recognized as the most comprehensive database available at an international level. The *US LCI* and the *US EI*, which is *Ecoinvent* with a US grid mix, were not used in this study because the *Ecoinvent* processes used were also adapted to a North-American context using a specific process that converted original electricity mix into North-American grid mix. Furthermore, the *US LCI* is difficult to use because of a lack of consistency among processes.

All the unit processes selected in this database were cradle-to-gate processes. All upstream processes are linked in current unit processes, covering the cradle-to-gate boundaries of the system. A report from the Consortium for Research on Renewable Industrial Materials (CORRIM) on prefinished engineered wood flooring manufacture has been used for the modeling of hardwood veneer production (Bergman and Bowe, 2011). The *Ecoinvent* report about LCI of chemicals has also served as a reference for created chemical processes for coating (Althaus et al., 2007). Table 1 presents the data gathered for the product LCI.

2.6.1. Raw materials acquisition and primary transformation

The input data for the first life cycle stage of the studied system was mainly gathered in the manufacture plant (Quebec, Canada). It

Table 1
Description of input data for the interior wooden door LCI.

Life cycle stage	Based on process[a]	Quantity	Source of data[b]
Raw materials	Particle board, indoor use, at plant/RER U (488 km)	0.0681 m^3	ecoinvent v2.2 modified (Qc grid mix (Hydro-Québec, 2012) and resin)
	Oriented strand board, at plant/RER U (2503 km)	0.00667 m^3	ecoinvent v2.2 modified (US grid mix and resin)
	Sawn timber, hardwood, raw, air/kiln dried, u = 10%, at plant/RER U (332 km)	0.000944 m^3	ecoinvent v2.2 modified (Qc grid mix (Hydro-Québec, 2012))
	Vinyl acetate, at plant/RER U (277 km)	0.792 kg	ecoinvent v2.2
	Veneer, hardwood, dry, at veneer mill (91 km)	1.4438 kg	Created (Bergman and Bowe, 2011)
	Fibreboard hard, at plant/RER U (3905 km)	0.0119 m^3	ecoinvent v2.2 modified (US grid mix)
	UV curable coating (114 km)	0.184 kg	Created (North-American grid mix (Itten et al., 2013))
	Transport, freight, rail, diesel/US U	44.0 t km	ecoinvent v2.2
	Transport, 53′ dry van (Class 8)/AM U AmN	27.52 t km	Created (National Research Council, 2010)
Manufacturing	Wood dust (co-product)	2.54 kg	
	Wood residue (co-product)	0.00054 m^3	
	Electricity mix/Quebec U	3.277 kWh	Created (Hydro-Québec, 2012)
	Emissions to air (indoor)		
	NMVOC, non-methane VOC, unspecified origin	*2.255 g*	*Substances*
Packaging	Electricity mix/Quebec U	0.098 kWh	Created (Hydro-Québec, 2012)
	Packaging film, LDPE, at plant/RER U (267 km)	118 g	ecoinvent v2.2
	Extrusion, plastic film/RER U (810 km)	1.6 g	ecoinvent v2.2 modified (input of LDPE, LLDPE and polybutadiene) (Doshi et al., 1996)
	EUR-flat pallet/RER U (12 km)	0.07875 p	ecoinvent v2.2
	Transport, 53′ dry van (Class 8)/AM U AmN CIRAIG	0.0328 t km	Created (National Research Council, 2010)
	Transport, van <3.5t/RER U	0.0203 t km	ecoinvent v2.2
	Waste to treatment:		
	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	*4 g*	*ecoinvent v2.2*
Shipping	Transport, 53′ dry van (Class 8)/AM U AmN CIRAIG (785 km)	41.2 t km	Created (National Research Council, 2010)
Usage	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	0.120 kg	ecoinvent v2.2
	Disposal, wood untreated, 20% water, to sanitary landfill/CH U	1.97 kg	ecoinvent v2.2
	Disposal, steel, 0% water, to inert material landfill/CH U	0.0154 kg	ecoinvent v2.2
	Transport, municipal waste collection, lorry 21t/CH U (60 km)	0.126 t km	ecoinvent v2.2
End-of-life	Transport, municipal waste collection, lorry 21t/CH U (60 km)	3.032 t km	ecoinvent v2.2
	Disposal, wood untreated, 20% water, to sanitary landfill/CH U	45.8 kg	ecoinvent v2.2
	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	4.29 kg	ecoinvent v2.2
	Disposal, polyurethane, 0.2% water, to sanitary landfill/CH U	0.214 kg	ecoinvent v2.2
	Disposal, emulsion paint, 0% water, to sanitary landfill/CH U	0.238 kg	ecoinvent v2.2

[a] Distances (in kilometers) next to raw materials and packaging materials indicate the transportation distance to the manufacturing plant.
[b] Data come from the database ecoinvent v2.2 or substances found in SimaPro. The unit processes found in ecoinvent v2.2 have been used as is, modified to fit the reality. New processes have also been created using ecoinvent v2.2 data.

was gathered during several visits to the plant. The collected data is about quantities, dimensions, and provenance of components and is presented in Table 1. Transportation distances of raw materials to the manufacturing plant are presented in parenthesis next to processes names.

For modeling the raw materials stage, processes found in the *Ecoinvent* 2.2 database have been used. The processes used in SimaPro to model the different components were based on original *Ecoinvent* unit processes, adapted to take into account the local electricity grid mix, product composition and transportation specificities. When the unit process did not exist, as it has been the case for UV coatings, or the hardwood veneer, Life Cycle Inventories (LCIs) and scientific literature have been used as described below.

For UV finishing, LCIs with detailed information did not exist. The unit process « Organic chemicals, at plant » is a rough estimation, so it has been chosen to use the chemical composition given by the Material Safety Data Sheet (MSDS). Most of the chemicals were not present in the database but the majority of reactant used to produce the chemicals was available. The main chemicals present in the list have been modeled using the online *Ullmann's Encyclopedia of Industrial Chemistry* (Adam et al., 2005; Penzel, 2000) for chemical reactions and standard values for chemicals production from the *Life Cycle Inventories of Chemicals* report from *Ecoinvent* (Althaus et al., 2007). Chemical reactions yields were approximated to 100% to simplify calculations. The different PVAc glues have been modeled using the “Vinyl Acetate, at plant” ecoinvent unit process as an approximation (Werner et al., 2007).

The hardwood veneer in the study has been modeled using the LCI report of the Consortium for Research on Renewable Industrial Materials (CORRIM) on the *Manufacturing of prefinished engineered wood flooring in the Eastern US* (Bergman and Bowe, 2011). Data quality and representativeness respect the ISO 14044 standard since the manufacturing practices in Eastern United States are similar to Quebec manufacturing practices and the technology presented is less than 5 years old. The electricity grid mix has been adapted to the situation in the province of Quebec.

The production of the Structural Composite Lumber (SCL) door parts have been approximated with the OSB manufacturing process from the database, since the panel manufacturing technology is similar. The adhesives used for the board bonding have been changed to fit the reality of the SCL parts technology. Manufacturing data for the particleboard, HDF and edges made from hardwood have been selected as is from the *Ecoinvent 2.2* database except for the electricity grid mix that has been adapted to fit the province of Quebec grid mix (particleboard and edges) and the US grid mix (HDF).

The Quebec electricity mix used was developed by the *Interuniversity Research Center for the Life Cycle of Products, Processes and Services* (CIRAIG, www.ciraig.org) in Montreal, Canada. The 2012 grid mix is a combination of hydroelectricity (96%), nuclear ebergy (2.1%) and thermal energy (0.10%). When the products were manufactured in the Province of Quebec, the Quebec grid mix was used. Otherwise, the model was set to transformed european based electricity profile into North American electricity profile (84% American grid mix, 11% Canadian grid mix, and 5% Mexican grid mix) to better suit the geographical LCA context.

2.6.2. Secondary production

The manufacturing of secondary wood products does not require a high amount of energy and materials. In fact, the basic steps of door manufacturing are mostly the assembly of door components, machining and packaging. The inputs and outputs of a door assembly are respectively electricity for the machinery (glue applicators, presses, trimming, sanding), PVAc leakage, dust and VOCs emission from glues.

The electricity grid mix used for the production stage is specific to the province of Quebec. The electricity mix is for the mostly hydroelectricity. The electrical consumption has been determined by the use of an ammeter. The measured data have then been calculated to fit the functional unit.

The amount of wood dust generated during sanding, trimming and machining was calculated based on the volume of wood removed. The production of dust has been credited as an avoided product that is in *Ecoinvent v2.2* "Industrial residue wood, from planning, air dried, u = 20%, at plant/RER U" softwood or hardwood depending on the part that was processed.

The emissions of VOCs for the different PVAc glues have been determined using data provided by the glue manufacturer.

2.6.3. Packaging and shipping

The door undergoes two types of packaging before being shipped. The first is to protect the door with an individual film. The second is to prepare pallets for shipping, where 20 doors are gathered and wrapped with stretch films. Transportation of packaging materials to the manufacturing plant, naming polyethylene films, stretch-films and pallets was considered. Transportation distances of packaging materials to the manufacturing plant are presented in parenthesis next to processes names.

The delivery of the product to the building site is done by road transport with a 53 ft truck of average loading (17.56 tons). To have a better approximation of distances, the main market location has been selected according to sales rate of the company for the studied product. The main location of delivery is the greater Toronto area (Ontario, Canada).

2.6.4. Usage

As mentioned in Section 2.3, it has been decided not to include the door frame, hinges, door handle or screws. The main reason was to focus on the as is manufactured product for further ecodesign strategies. The use of interior doors, in general, does not require energy or cleaning products. Even if it happens that doors are

Table 2
Description of IMPACT2002+ and ReCiPe methodologies.

Impact assessment methodology	Midpoint categories	Endpoint/Damage categories
Impact 2002+	Carcinogens	Human Health (DALY)[a]
	Non-carcinogens	
	Respiratory organics	
	Ionizing radiation	
	Ozone layer depletion	
	Respiratory organics	
	Aquatic ecotoxicity	Ecosystem Quality (PDF.m^2.yr)[b]
	Terrestrial ecotoxicity	
	Terrestrial acid/nutria	
	Land occupation	
	Aquatic acidification[f]	
	Aquatic eutrophication[f]	
	Global warming	Climate Change (kg CO_2 eq)
	Non-renewable energy	Resources (MJ primary)[c]
	Mineral extraction	
ReCiPe	Climate Change	Human Health (DALY)
	Ozone depletion	
	Human toxicity	
	Photochemical oxidant formation	
	Particulate matter formation	
	Ionising radiation	
	Terrestrial acidification	Ecosystems (Species.yr)[d]
	Freshwater eutrophication	
	Marine eutrophication	
	Terrestrial ecotoxicity	
	Freshwater ecotoxicity	
	Marine ecotoxicity	
	Agricultural land occupation	
	Urban land occupation	
	Natural land occupation	
	Water depletion	
	Metal depletion	Resources ($)[e]
	Fossil depletion	

[a] DALY: Disability-Adjusted loss of Life Years. This unit characterizes the disease severity, accounting for both mortality and morbidity.
[b] PDF.m^2.y: Potentially Disappeared Fraction of species over one m^2 during one year. This unit represents the fraction of species disappeared on 1m^2 of earth surface during one year.
[c] MJ primary: Mega Joule primary. The unit measures the amount of energy extracted or needed to extract the resource.
[d] Species.yr: The unit represents the loss of species diversity during one year.
[e] Dollars unit: The unit symbolizes the resource cost according to its availability that is assumed to increase.
[f] Aquatic acidification and aquatic eutrophication are not taken into account for the calculation of Ecosystem Quality damage category in the version of IMPACT 2002+included in SimaPro.

Table 3
Equivalences between life cycle stages and names of processes modeled in SimaPro.

Name of stages presented in pie charts	Name of process modeled in SimaPro network views
Raw Materials	Transportation of raw materials
	Door manufacturing (raw materials)
Manufacturing	Door manufacturing (energy and waste flows)
Packaging	Packaging
Shipping	Transportation to site
Usage	Door packaging disposal
End-of-life	Door disposal at end-of-life

cleaned up, it would hardly happen more than a few times a year. However, since the use of a new door implies the removal of all packaging, their disposal has been considered in this stage. The transportation, to a landfill site, of plastics and pallet has been included in the LCA. Packaging wastes are transported with a municipal waste collection truck at approximately 60 km from the construction site. The nearest landfill site is approximately 50 km far from downtown Toronto. However, it has been decided to set the distance at 60 km to represent actual routes.

2.6.5. End-of-life

At the end of their lives, most wood products are disposed into landfills in Canada (Statistics Canada, 2005). Therefore, it has been decided to consider this scenario in this study. The transportation from the building site to the landfill is considered in this stage. As mentioned in the previous section, the nearest landfill site is approximately 60 km far from downtown Toronto. The door is transported to the landfill with a municipal waste collection truck. The behavior of specific wood products in landfill is not well documented (Wang et al., 2011; Ximenes et al., 2008). The *Ecoinvent* database does not include wood products in its landfill processes, only "wood untreated". To estimate the actual situation, different processes have been used as an approximation to the composite materials present in the boards and the door and the UV curable varnish (Table 1). Disposal of boards have been divided into disposal of wood untreated, that simulates wood particles/chips and disposal of polyurethane that simulates the resin. The PVAc glue was approximated as disposal of plastic mixture and the UV varnish disposal as disposal of emulsion paint. Emissions due to landfilling are included in the *Ecoinvent* process.

2.6.6. Transportation details

Road transportation is used for the most part but there is also rail transport. The road transportation has been modeled using a unit process from the CIRAIG to approximate the road fleet in North America, since the utilization of trucks is not the same in Europe. The process simulates a 53 ft long truck that has an average truck load of 17.56 tons and a maximum of 25 tons. The rail freight transport modeling is based on the US diesel rail freight model from the database, since the rail transportation part takes place in the US.

2.7. Life Cycle Impact Assessment (lcia)

LCIA purpose is to provide an interpretation of LCI results so as to better understand their environmental significance (ISO, 2006b). Since each impact assessment methodology does not assess LCI data like any other, professionals agree on the use of two or more impact assessment methods to support the findings. In this study, IMPACT 2002+ was chosen (Humbert et al., 2005) as main methodology and the ReCiPe model with the Hierarchist (H) perspective (Goedkoop et al., 2012) as supportive methodology. The H perspective has been chosen since it is based on the most common policy principles with regards to time-frame and other issues. A brief description of their respective categories is presented in Table 2.

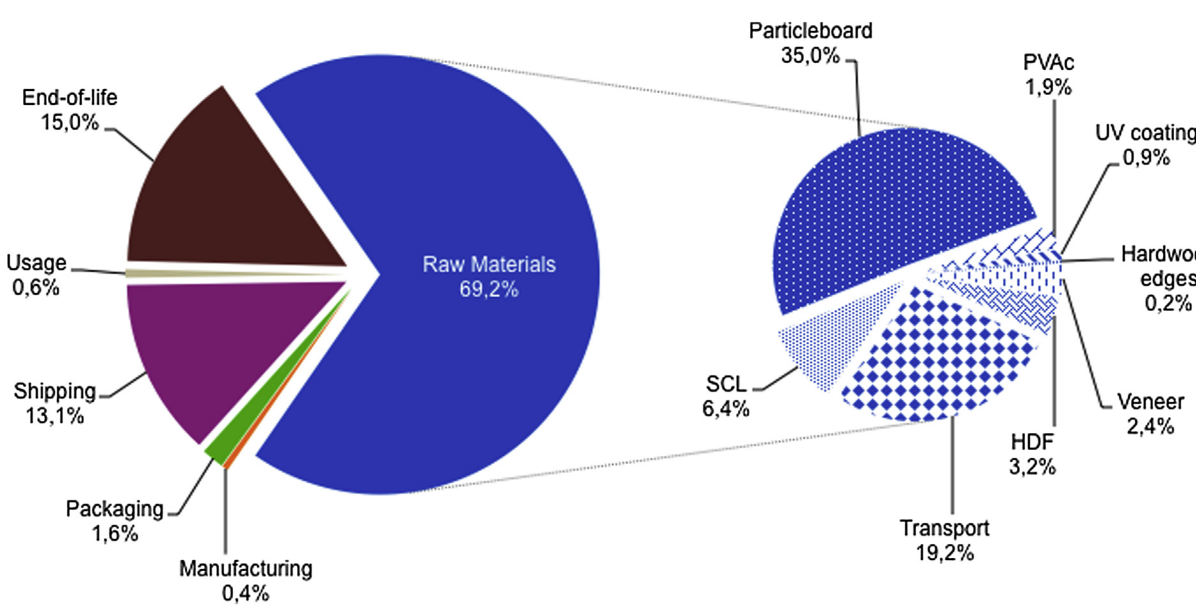

Fig. 2. Contributions of life cycle stages to the environmental impacts of the door and details for the main contributor according to the Human Health damage category (IMPACT 2002+).

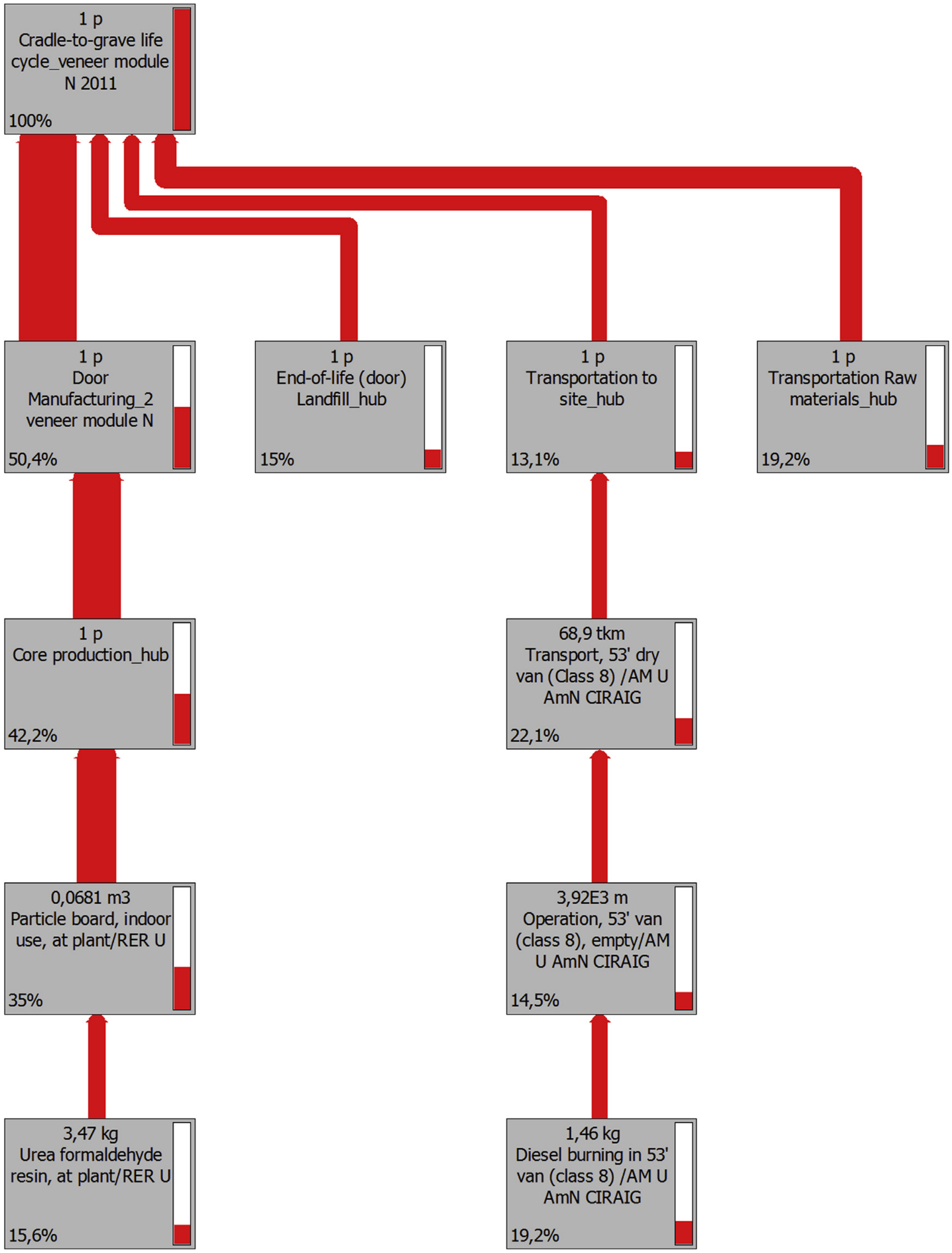

Fig. 3. SimaPro network view of the *Human Health* damage category. Contributions cut-off set at 15%.

Impact 2002+ combines a midpoint/endpoint (or damage) approach, linking all types of life cycle inventory results (elementary flows and other interventions) via fourteen midpoint categories and four damage categories. Some characterization factors are taken from the methodology Impact 2002 – IMPact Assessment of Chemical Toxics and others are adapted from existing methods, such as Eco-indicator 99, CML 2001, IPCC and the Cumulative Energy Demand (Humbert et al., 2005).

ReCiPe is the successor of the Eco-indicator 99 and CML-IA methods. ReCiPe 2008 implements both strategies and has eighteen midpoints and three damage categories. It comprises two sets of impact categories with associated sets of characterization factors. (Goedkoop et al., 2012).

During the impact assessment step, data obtained in the software have been exported to *Excel* for a thorough analysis and its interpretation led to a rearrangement of LCIA data.

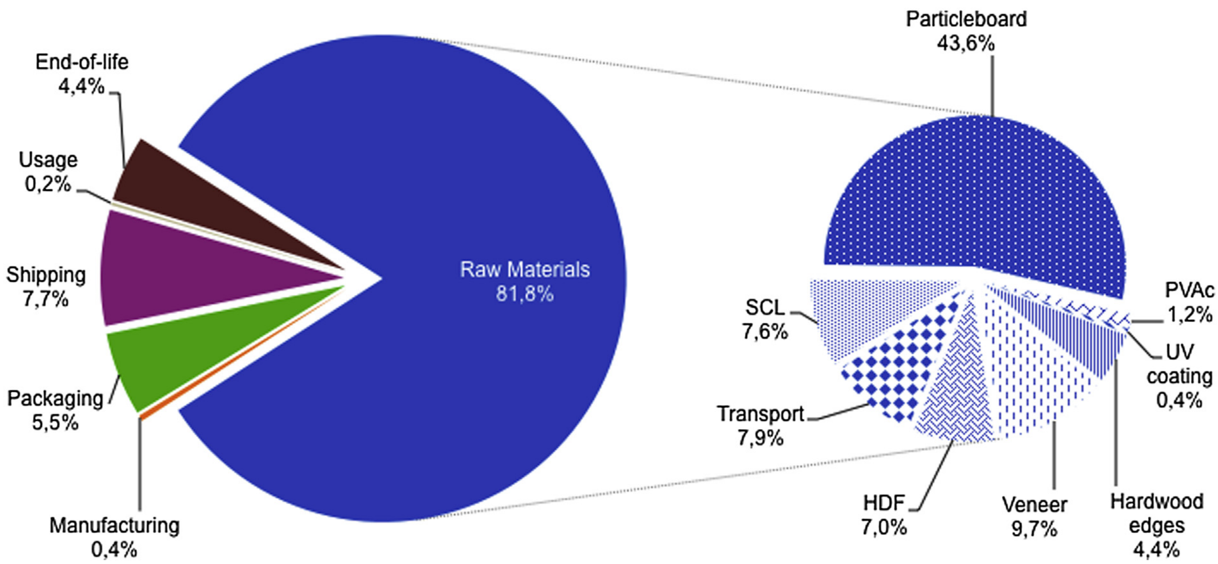

Fig. 4. Contributions of life cycle stages to the environmental impacts of the door and details for the main contributor according to the Ecosystem Quality damage category (IMPACT 2002+).

3. Results

Results from this LCA for the door system are discussed at a damage level for simplified data treatment and comprehension. The present section pictures the contribution of the door components to the total environmental impact of the product, using the four endpoint/damage categories of the methodology *IMPACT 2002+*. These are human health, ecosystem quality, climate change and resources.

The results are also discussed at a midpoint level for a deeper understanding of the environmental impacts and are showed in the network view. This view enables to highlight where specific issues are located in the network of processes. Table 3 displays the equivalences between the life cycle stage names used in the results figures and the processes names that can be read in SimaPro network view. The contribution percentages displayed in the network view are sometimes superior to the ones found in their respective downstream processes. A network contains loops and one process can be used by others as well, so their contributions may show up higher. In the software, the system has been divided in 6 processes as described in Table 3. *Door manufacturing* includes both stages of Manufacturing and Raw materials, whereas *Transportation of raw materials* is included in the Raw materials stage. The other life cycle stages remain unchanged; only their names have been substituted.

3.1. Damages on human health

The *Human Health* category is largely influenced by the raw materials with 69% of the total impact (Fig. 2). The second most contributive stage is the end-of-life with 15%, followed closely by the door shipping to the building site, with13%. Considering these results, it is obvious that the three other stages do not influence much the score of the door in this damage category. The least contribution to this damage category is attributed to the manufacturing stage.

Taking a closer look at the detailed pie on the right-hand side, it is possible to see both what processes are involved and their importance in percentage. The particleboard is to be the main component of the raw materials score, representing 35% of the raw material impact. This is half of the raw material value. In second place, the transport of raw materials to the plant, with 19%, accounts for about a third of the raw material value. Referring to Table 2 for *IMPACT 2002+*, the midpoint categories linked to this damage category are carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion and respiratory organics. At this level of characterization, raw materials exceed 50% of the total contributions for each category. Their single largest contribution is of 87% to non-carcinogens. Packaging has a low contribution to human health and it is reflected in the midpoint categories, representing 2%–5% maximum of carcinogens for example. The shipping to the building site reaches a peak in the respiratory organics category with about 13%, which is representative of road transportation. The usage phase that entails landfilling of all door packaging has no significant variation across the six midpoint categories. Finally, landfilling has a higher contribution, by order of importance, to respiratory organics, respiratory inorganics and ozone layer depletion. Those indicators are mostly related to the impacts from the road transportation of the door to the landfill site for a distance of 60 km and the impacts of the emissions liquid or gaseous coming from the landfilled product.

Fig. 3 presents the network view of our system with cradle-to-grave boundaries. The view of the processes contributions to human health has been restricted to 15% and more for a straightforward understanding but also because of space issues. From the network point of view, it becomes obvious that the particleboard has the largest contribution. It counts for more than 75% of core production impacts (42% out of 50%). The core production process includes manufacturing energy and waste flows needed for core production and core raw materials (cf. Table 1). The impacts on human health for a particleboard are half related to the production of the Urea Formaldehyde resin (UF) and less than a half related to the use of wood chips as energy in furnace. The impact of UF production is noticeably affected by the production of urea more than formaldehyde. It is also not surprising that the transportation of raw materials contributes for more than 15% in human health damage (19.2%). Road transportation in general is related to airborne emissions of particulates matter and other NO_x (Insee, 2012).

Please cite this article in press as: Cobut, A., et al., The environmental footprint of interior wood doors in non-residential buildings — part 1: life cycle assessment, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.04.079

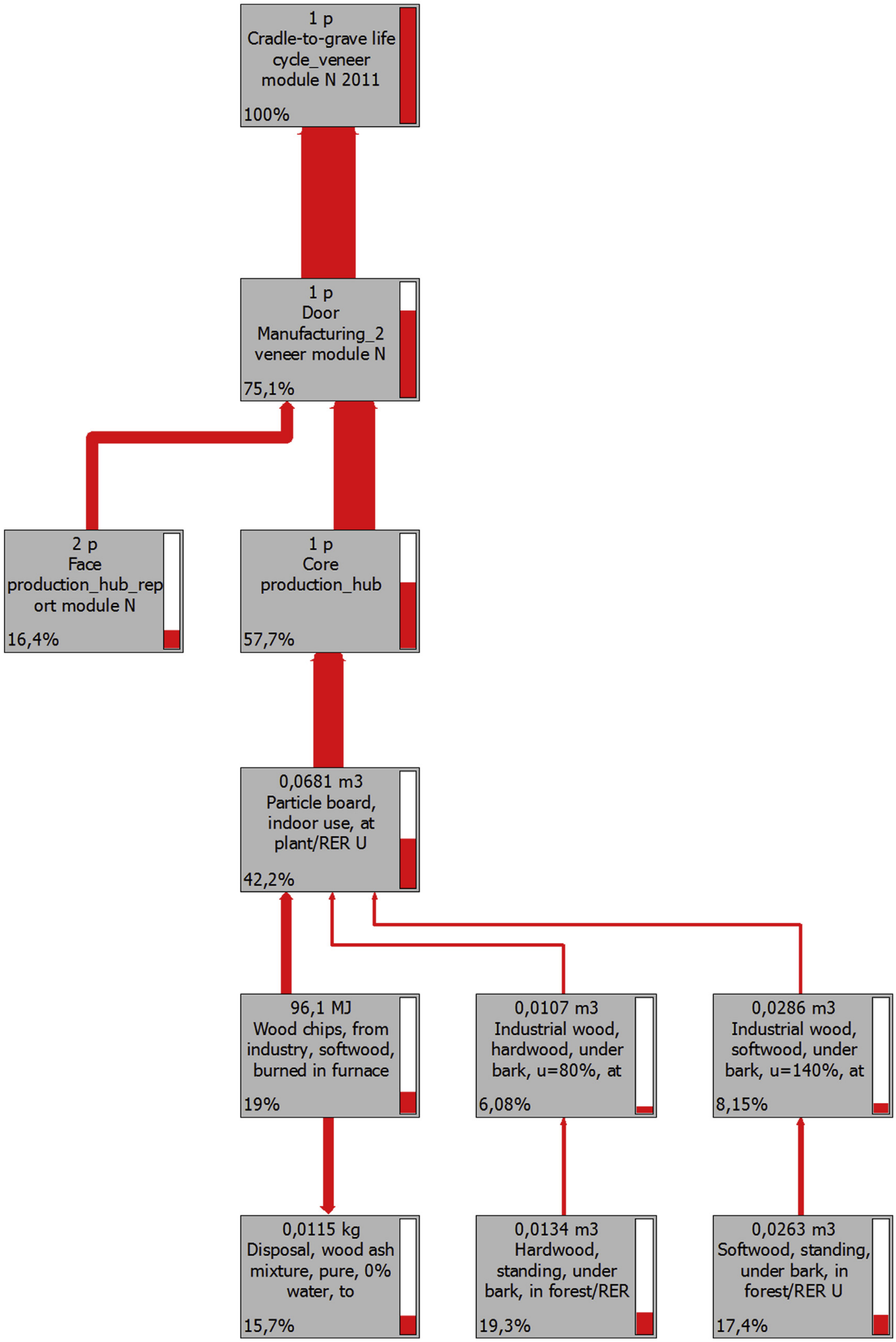

Fig. 5. SimaPro network view of the *Ecosystem Quality* damage category. Contributions cut-off set at 15%.

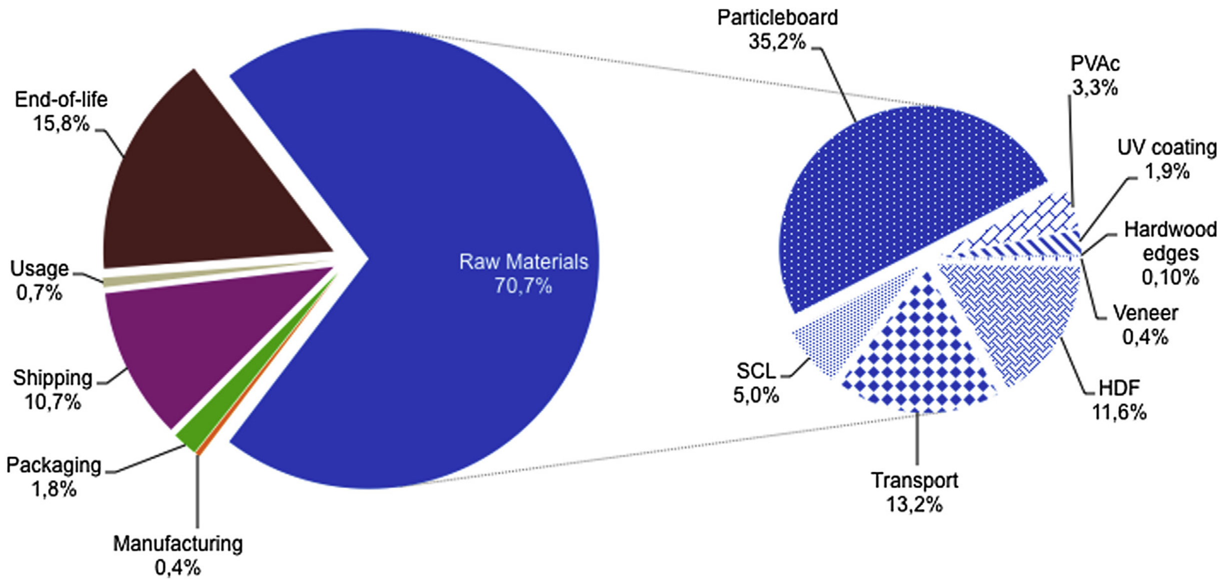

Fig. 6. Contributions of life cycle stages to the environmental impacts of the door and details for the main contributor according to the Climate Change damage category of IMPACT 2002+.

3.2. Damages on ecosystem quality

The *Ecosystem Quality* category is even more influenced by raw materials with 82% of the global score (Fig. 4). The other stages that cannot yet be neglected are the shipping, the packaging and the door end-of-life, with 8%, 6% and 4%, respectively. Taking a closer look at the detailed pie chart for raw materials, it can be seen that the particleboard is responsible for half of the impacts of all raw materials, their transportation included with 44% out of 82%. The veneer production comes in second place for its contribution to raw materials impacts with nearly 10%. Third place is occupied by transport with a percentage of 8%. The lowest percentage is provided by the use phase.

In *IMPACT 2002+* the midpoint categories linked to this damage category are aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification and nutrification, and land occupation (Table 2). Raw materials participate once more at a maximum to these four midpoint categories. Its highest contribution in ecosystem quality related indicators is in land occupation (in m^2 organic arable land. yr). It can be interpreted by the fact that a lot of products based on wood are used, especially veneer and hardwood edges that need timber of larger size and not particles that are generally by-products from primary transformation industries. Similarly, the production of HDF and particleboard is half based on industrial residue and half based on virgin fiber. Of course, the production of wood requires industrial interventions on vast areas of forested land but the characterization factors for land occupation in *IMPACT 2002+* comes from *Eco-indicator 99* that are based on a model of land-use change in Switzerland between 1850 and today. It is hard to believe that this is representative of the situation of the production of wood from current Canadian forest management. This issue deserves further investigation and researchers have been already working on the problem in order to take into account a broader set of ecosystems and ecosystem services (de Baan et al., 2013; Koellner et al., 2013). The manufacturing and usage stages have few impacts on those categories compared to the others. Packaging has a greater impact on land occupation due to the fact that this phase uses pallets made from wood. The impacts related to the shipping of the door are elevated for terrestrial acidification and nutrification, which is logical since the emissions of NO_x contribute greatly to this indicator. For that reason, the transport of raw materials possesses a significant percentage in this indicator category. The greatest impact of landfilling of the door is related to terrestrial acidification/nutrification because of the transport from the site to the landfill site.

Fig. 5 illustrates the network view for the damage to the quality of ecosystems. From this figure it can be seen that the core production have larger impacts on ecosystem quality with 58% out of 75% considering the door manufacturing process. The particleboard once again contributes for three-quarter of the core production impacts. The use of wood chips for energy seems to have a sizeable contribution, mainly caused by the disposal of wood ash. The two processes based on industrial wood are shown even if they are below 15% because the underlying processes for hardwood and softwood are higher than 15%. This illustrates how wood products have a significant impact on ecosystem quality but again, based on an impact analysis tool developed in the Swiss context. This again, should be further evaluated with a regionalized process allowing for the modeling of the Canadian forest management and wood products production contexts. However, urea formaldehyde resin production, not visible in Fig. 5, accounts for 7%, which is a bit higher than the contribution of industrial wood. The impacts from faces production cannot yet be neglected. Their contribution is as high as 16% and is mainly caused by the veneer manufacturing at 57% and by HDF production at 41%.

3.3. Damages on climate change

For the *Climate Change* category, raw materials provide, as in the two previous cases, the highest input with 71% (Fig. 6). The particleboard is responsible, once again, for half of the raw materials impacts on this damage category, with 35%, followed by transportation and HDF manufacturing with 13% and 12% respectively. The second life cycle stage that takes a great part in climate change impacts is landfilling of the door with 16%. As concerns shipping, it is in third contribution with 11%. The manufacturing stage shows the smallest contribution.

In Table 2 for *IMPACT 2002+*, the midpoint category linked to *Climate Change* damage is global warming expressed in kg CO_2 eq.

Please cite this article in press as: Cobut, A., et al., The environmental footprint of interior wood doors in non-residential buildings – part 1: life cycle assessment, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.04.079

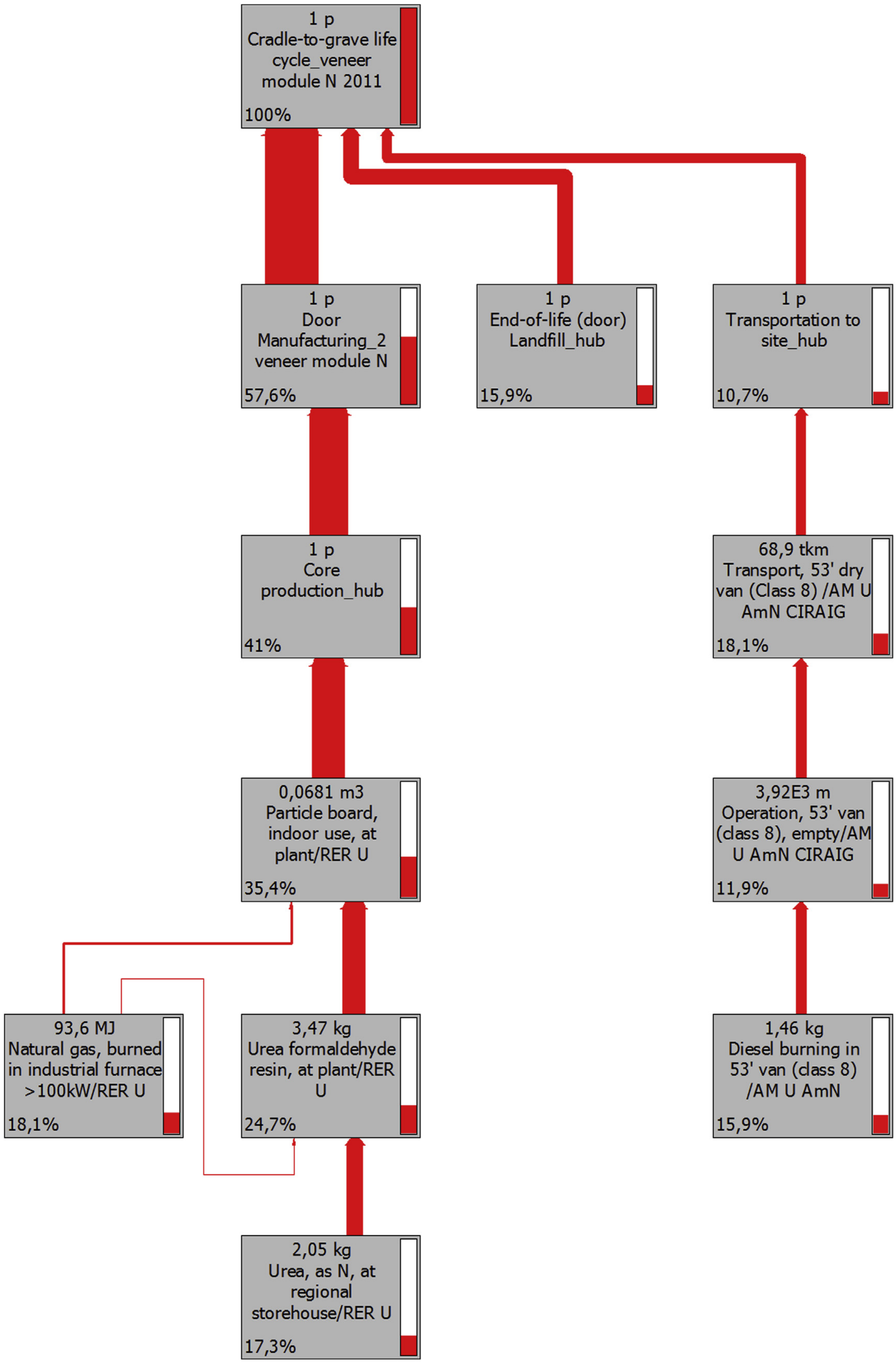

Fig. 7. SimaPro network view of the *Climate Change* damage category. Contribution cut-off at 15%.

The main substances influencing this indicator are greenhouse gases (GHG) such as CO_2, CH_4, N_2O or CO (Humbert et al., 2005). Looking at Fig. 7 enables further analysis of Fig. 6 data. The production of particleboard was accountable for half of raw materials impact; the end-of-life stage had the second highest percentage, and shipping the third place. The production of UF is involved for 70% of particleboard impacts. The production of urea is largely involved in the network and can be sourced in the carbon monoxide, methane and ammonia emissions from the production process. Their impacts may be also related to the use of natural gas in their production chains as a heat source. A part of the end-of-life process seems to come from the transportation as shown earlier. The same goes for the transportation processes where the impacts are linked to the consumption of diesel.

3.4. Damages on resources

For the door system, the impacts on the *Resources* damage Category show up mostly in the raw materials again (Fig. 8). Their impacts on resources are as important as 79%. In the detailed pie on the right hand side, the particleboard contributes for 42% to the total raw materials impact. The second and third most elevated percentages belong to HDF production at 11% and transportation at 10%. The PVAc is also a relatively high contributor, with a percentage of around 7%. The other raw materials together contribute for less than 10%. The end-of-life and shipping are roughly 10% and 8% respectively. The minimum contribution is from the usage phase.

Referring to Table 2 for *IMPACT 2002+*, the midpoint categories linked to this damage category are non-renewable energy and mineral extraction. Therefore, the bigger the impact of a process is, the greater the amount of fossil fuels and/or minerals will be needed to operate it. The raw materials acquisition and transformation stage is the most contributive to those two indicators. Raw materials highest percentage is found for the indicator mineral extraction just below 90%. In fact, their transportation is partly based on freight transportation (44 t km) for HDF acquisition by rails. Road transportation has a lesser impact on mineral extraction than rail freight but minerals are needed for road building and maintenance such as in concrete, gravels and bitumen. Road transportation is as high as 27.5 t km. The manufacturing and usage phase are the lowest contributions in both midpoint categories. Packaging has almost the same percentage values in both categories but is slightly higher for mineral extraction because of the presence of steel in palettes production. Shipping is higher in the use of non-renewable energy. Regarding the end-of-life, its impact is doubled for non-renewable energy compared to mineral extractions, caused by the transport of the door to the landfill site.

The network display for this damage category appears in Fig. 9. As previously, the contributions shown are those exceeding 15%. Once again the thickest arrow comes from the particleboard process. This time, the production of UF accounts for almost 75% of particleboard impacts on resources. It seems that natural gas is a common denominator to those impacts, as well as HDF production impacts. Besides, just under 15%, the faces fabrication contributes for 14% of door manufacturing impacts.

4. Discussion

In the four damage categories, the raw materials stage takes a significant fraction of the score. Across the four damage categories, it is clear that particleboard has the greatest impacts mainly due to the use of UF resin during its manufacturing. These results are well illustrated by network displays for the four damage categories. Beyond the fact, that UF resin has an important in the particleboard environmental impacts, it must be mentioned that the particleboard is the biggest component of the door, in terms of weight and volume. The faces have also a non-negligible role to play in the door total impact, owing to the production of HDF using natural gas. The other processes, linked to the production of forest products, have a much lesser impact. In a North American report, it is explained that the forest products industry has made a great improvement in waste management (Bowyer, 2012). In terms of wood use, it has become a zero-waste industry with a percentage of wood waste varying from 0.14% to 1.5%. This is due to both lumber yield improvement in sawmills and the existence of markets for coproducts. In addition, the portion of manufacturing process energy derived from residual wood was estimated at 76% for lumber, 90% for plywood and 81% for OSB by 2005 (Meil et al., 2007). The residues that do still remain at mill locations are primarily bark that can be used as mulch, energy, or compost (Lama, 2011).

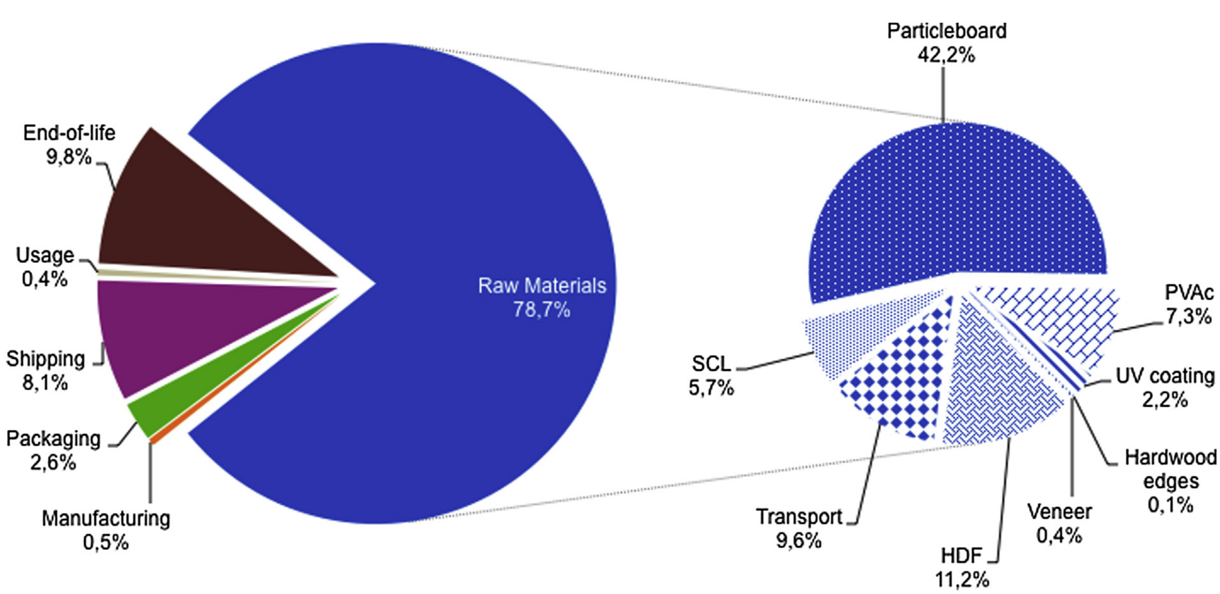

Fig. 8. Contributions of life cycle stages to the environmental impacts of the door and details for the main contributor according to the Climate Change damage category of IMPACT 2002+.

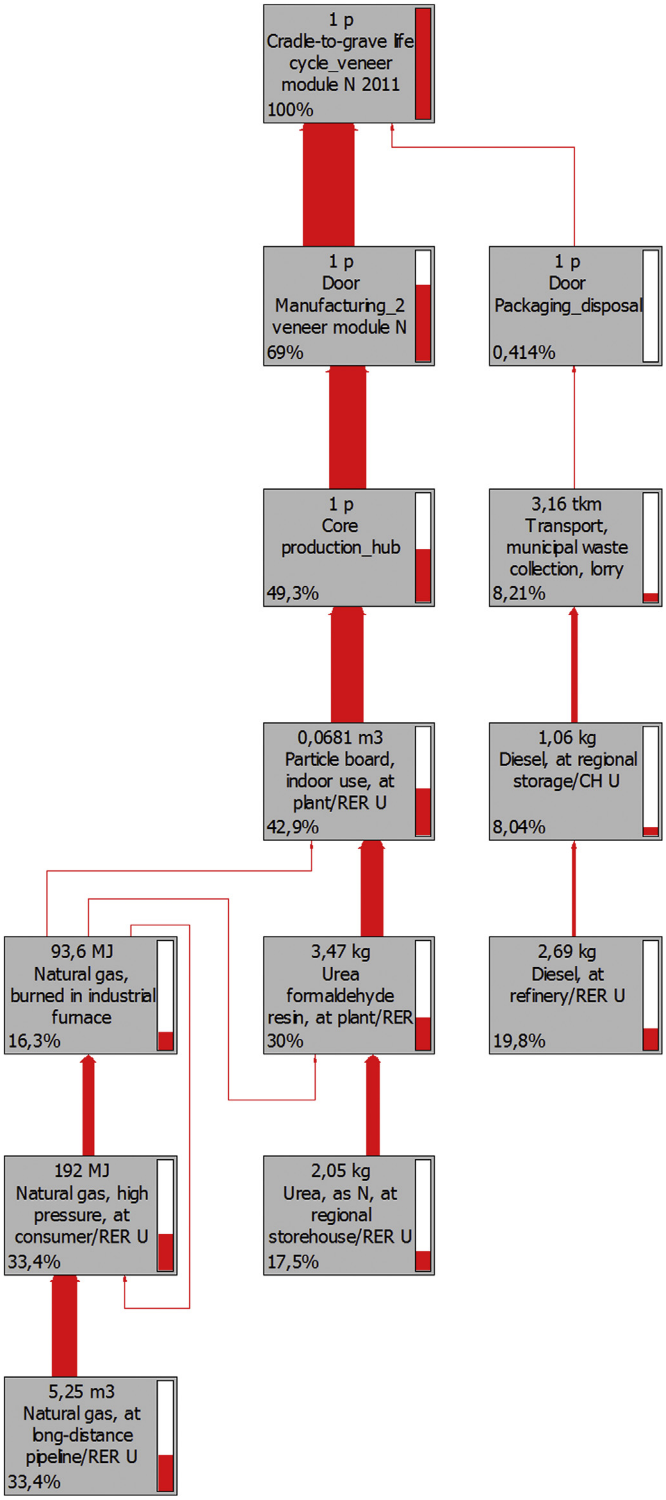

Fig. 9. SimaPro Network view of the *Resources* damage category. Contributions cut-off set at 15%.

Moreover, the end-of-life of our system has the second most considerable impacts on the studied system, partly due to the distance from the construction site to the landfill site that has been estimated at 60 km from Toronto downtown. In the same line of ideas, it is not surprising to see that transportation to site is the third most influential stage on our system total environmental impacts. However, this is a fact for most wood based products manufacturers based in distant areas. Speaking of transportation, the raw materials stage has also to deal with the impact of transportation that is substantial compared to the others components. Actually, HDF and SCL boards are shipped from USA to the manufacturing site in the province of Quebec, Canada.

The manufacturing stage has very little impacts compared to the other life cycle stages because the main source of energy used on site is hydroelectricity and the main machinery for door production runs with electricity (presses, machining, UV line, packaging machines, trimming). Wood waste, from boards sanding or door trimming, is bought by a board manufacturing plant in the province.

Finally, the results obtained with the impact assessment methodology *ReCiPe Hierarchist* confirmed trends observed with *IMPACT 2002+*. The first contributor to the door total environmental impacts is the raw materials stage with 68% of human health impacts (in DALY), 81% of ecosystems impacts (in species. yr) and nearly 79% of resources impacts (in $). Particleboard still plays the major role in all three damage categories. The end-of-life contributes for 20% of human health impacts, 6% of ecosystems impacts and 10% of resources impacts. Shipping has the third place with 10% of human health impacts, 3% of ecosystems impacts and 8% of resources impacts. Notwithstanding the fact that landfilling and shipping have greater impacts than packaging in 2 out of 3 damage categories, packaging arrives second for impacts on ecosystems surely because of wood pallet utilization.

4.1. Sensitivity analysis

A sensitivity analysis has been performed on transportation parameters since it has an important contribution to the environmental impacts of the door life cycle. On one hand, the impact of distances has been studied by varying all transportation distances by ±25% (road and rail freight). It has been observed that the main conclusions of the study were maintained. On the other hand, the impact of truck loadings for transportation to site of the final product has been studied by varying the amount of load by ±25%. Here again, the main conclusions of the study were maintained. The original truck load was set to an average of 17.56 tons while the maximum is 25 tons for 53 ft truck.

Decreasing the allocation factor preset in *Ecoinvent v2.2* for roundwood (86% for softwood and 82% for hardwood) by 5% and 10% did not change the main observations made from the door LCA results.

Considering the singularity of the province of Quebec grid mix mostly based on hydroelectricity, it has been decided to perform a sensitivity analysis using the electricity grid mix of the United States. While it has been observed that the manufacturing stage of the door life cycle was the less contributive stage to total environmental impacts under the province of Quebec grid mix, another observation has been drawn when considering the US grid mix, Contributions of the manufacturing stage under the US grid mix to the total environmental impacts have increased ranging from −0.38% and 0.46% (Qc grid mix) to 1.3% and 6.2% (US grid mix). The manufacturing stage becomes the fourth most contributive stage behind raw materials, transportation and end-of-life.

5. Conclusions

This study establishes the environmental profile, from cradle to grave, of a wood interior door used in non-residential buildings using LCA. Particleboard manufacturing has proven to be the most prominent source of impact in the door system. Urea Formaldehyde, used as a binder in the particleboard production, is the main contributor to particleboard impacts for three out of four damage

Please cite this article in press as: Cobut, A., et al., The environmental footprint of interior wood doors in non-residential buildings — part 1: life cycle assessment, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.04.079

categories. The transportation, both concerning raw materials and shipping, has a large influence on the door life cycle impacts. Shipping is a central issue for wood products manufacturers located in distant areas. This is likely to remain the same since there are no other options. The landfilling is responsible for as much impact as transportation, especially due to the distance between the building site and the landfill site.

However, the door manufacturing stage has a small contribution to the door life cycle impacts because it uses hydroelectricity as main source of energy. The score of wood products such as SCL, hardwood edges or veneer can be explained by their low volume compared to the particleboard and by the waste management reality of the forest products industry. Numbers have been given for the North American industry but it is reasonable to consider a similar situation is in place in European countries.

The obtained results have permitted to target the main sources of environmental impacts in the product life cycle. They are raw materials, end-of-life and transportation linked to both raw materials and shipment. These sources could be investigated further and serve as a basis for the purpose of ecodesign. Since UF resin was the main contributor to raw materials impacts, alternatives should be addressed. Similarly, alternatives for the landfilling and transportation stages could be investigated.

6. Limitations of the study

The study findings are based on the North-American context. The manufacturing stage data is Quebec specific, where the electricity grid mix is dominated by hydroelectricity. For the stages other than manufacturing, the used electricity grid mix was North American rather than from Quebec because products are rarely entirely engineered or sourced from local suppliers. We had limited access to LCI data for UV finishing, which is a proprietary process. Furthermore another limitation would be the impact assessment performed by *IMPACT 2002+* that is mostly based on the Swiss land-use situation that represents the beginning of a steady decline of species density in Europe today. The creation of regionalized characterization factors for land-use should be considered on a global scale because of the diversity of ecosystems and of forest managements systems. The absence of certified wood processes, taking into account and tracking wood from sustainable forest management in current inventory databases, like *Ecoinvent*, also limits the possibilities and proper modeling of the Canadian forest situation. In addition, the use of *Ecoinvent v2.2* data, which is based on European processes, may also add further limitations in our results even though the LCI data has been as much as possible adapted to a North-American context.

6.1. Biogenic carbon

The carbon stored in wood products has not been calculated separately and added in our model. The *Ecoinvent* database, used for the LCA purpose, has been selected to choose wood products processes from. However, the carbon allocation correction developed by the database to take into account the carbon storage in wood products is not relayed to LCA results since *IMPACT 2002+* did not take into account carbon intake when calculating environmental impacts which is consistent with almost all environmental impact assessment methodologies available. Therefore, by accounting for carbon intake from forest and then storage in wood products, the results will vary from the presented results.

Wood products in landfills have a slow rate of decomposition and deposition in landfills is widely considered as a mean to enhance carbon storage assuming that landfill gases are recovered properly (Larson et al., 2012; Micales and Skog, 1997; Sathre and O'Connor, 2010; Skog, 2008). Nevertheless, in this study, the door deposition in a sanitary landfill was not considered as carbon storage due to a lack of field data. Then, it is fair to prospect that the accounting of carbon storage during landfilling may change the environmental impacts contribution of the end-of-life to the total score of the door by lessening its impacts contribution and maybe balancing door waste transportation impacts to landfill site.

Acknowledgements

The authors would like to thank the NSERC (CRD 386935) and FPInnovations for the funding of this research project, the persons, at Lambton Doors, that collaborate with us and made this case study possible. Finally, the authors would like to thank employees at FPInnovations for its support and help and also people, at CIRAIG, that have helped throughout the LCA process.

References

Adam, N., Avar, G., Blankenheim, H., Friederichs, W., Giersig, M., Weigand, E., Halfmann, M., Wittbecker, F.-W., Larimer, D.-R., Maier, U., Meyer-Ahrens, S., Noble, K.-L., Wussow, H.-G., 2005. Polyurethanes. In: Elvers, B. (Ed.), Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH, Weinheim.

Althaus, H.-J., Chudacoff, M., Hischier, R., Jungbluth, N., Osses, M., Primas, A., 2007. Life Cycle Inventories of Chemicals, Ecoinvent. report no8. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Barker, T., Bashmakov, I., Alharthi, A., Amann, M., Cifuentes, L., Drexhage, J., Duau, M., Edenhofer, O., Flannery, B., Grubb, M., Hoogwijk, M., Ibitoye, F.I., Jepma, C.J., Pizer, W.A., Yamaji, K., 2007. Mitigation from a cross-sectoral perspective. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Béchard, C., 2008. Stratégie d'utilisation du bois dans la construction au Québec. In: Ministère des Ressources Naturelles et de la Faune. Gouvernement du Québec, p. 20.

Bergman, R., Bowe, S., 2011. Life-cycle Inventory of Manufacturing Prefinished Engineered Wood Flooring in the Eastern United States, Module N. CORRIM, p. 47.

Bowyer, J.L., 2012. Utilization of Harvested Wood by the North American Forest Products Industry. Dovetail Partners, Inc., Minneapolis, MN, p. 22.

Bribián, Z.I., Capilla, V.A., Usón, A.A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140.

de Baan, L., Alkemade, R., Koellner, T., 2013. Land use impacts on biodiversity in LCA: a global approach. Int. J. Life Cycle Assess. 18, 1216–1230.

Doshi, A.G., Kos, F.T., Salkar, D.C., 1996. High Stretch Film for Pallet Wrapping. Borden Inc, Columbus, Ohio, USA, p. 6. C08J 3/18 ed.

Drouin, M., Blanchet, P., Beauregard, R., 2012. Characterization of the design function in the appearance wood products for nonresidential buildings: a conceptual framework. Int. J. Des. Objects 6, 1–19.

Esin, T., 2007. A study regarding the environmental impact analysis of the building materials production process (in Turkey). Build. Environ. 42, 3860–3871.

Goedkoop, M., Heijungs, R., Huijbregts, M.A.J., De Schryver, A., Struijs, J., van Zelm, R., 2012. ReCiPe 2008, a Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, Revised First ed. PRé Consultants, CML University of Leiden, Radboud University Nijmegen, RIVM, p. 126.

Guidice, F., La Rosa, G., Risitano, A., 2006. Product Design for the Environment: a Life Cycle Approach. CRC Press - Taylor & Francis Group, Boca Raton, FL, USA.

Humbert, S., Margni, M., Jolliet, O., 2005. IMPACT 2002+: User Guide. Draft for Version 2.1. Industrial Ecology & Life Cycle Systems Group, GECOS. Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland, p. 36.

Insee, 2012. Emissions de Polluants des Transports Routiers. Institut national de la statistique et des études économiques.

ISO, 2006a. ISO 14040 Environmental Management – Life Cycle Assessment – Principle and Framework. International Organisation for Standardisation, Geneva, Switzerland, p. 20.

ISO, 2006b. ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organisation for Standardisation, Geneva, Switzerland, p. 46.

Knight, L., Huff, M., Stockhausen, J., 2005. Comparing energy use and environmental emissions of reinforced wood doors and steel doors. For. Prod. J. 55, 48–52.

Koellner, T., de Baan, L., Beck, T., Brandão, M., Civit, B., Margni, M., Milà i Canals, L., Saad, R., Maia de Souza, D., Müller-Wenk, R., 2013. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle Assess. 18, 1188–1202.

Lama, I., 2011. Wood residue availability in Canada. In: International Bioenergy and Bioproducts Conference, Atlanta, GA.
Larson, C., Chatellier, J., Lifset, R., Graedel, T., 2012. Role of forest products in the global carbon cycle: from the forest to final disposal. In: Ashton, M., Tyrrell, M., Spalding, D., Gentry, B. (Eds.), Managing Forest Carbon in a Changing Climate. Springer, pp. 257–282.
Levine, M., Ürge-Vorsatz, D., Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., Mongameli Mehlwana, A., Mirasgedis, S., Novikova, A., Rilling, J., Yoshino, H., 2007. Residential and commercial buildings. In climate change 2007: mitigation. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Meil, J., Wilson, J., O'Connor, J., Dangerfield, J., 2007. An assessment of wood product processing technology advancements between the CORRIM I and II studies. For. Prod. J. 57, 83–89.
Micales, J., Skog, K., 1997. The decomposition of forest products in landfills. Int. Biodeterior. Biodegrad. 39, 145–158.
O'Connor, J., 2009. Considerations for Environmental Footprinting of Wood Doors. FPInnovations-Forintek, Vancouver, BC, Canada, p. 28.
Penzel, E., 2000. Polyacrylates. In: Elvers, B. (Ed.), Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH, Weinheim.
Pigosso, D.C.A., Zanette, E.T., Filho, A.G., Ometto, A.R., R, H., 2010. Ecodesign methods focused on remanufacturing. J. Clean. Prod. 18, 21–31.
Sathre, R., O'Connor, J., 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ. Sci. Policy 13, 104–114.
Skog, K.E., 2008. Sequestration of carbon in harvested wood products for the United States. For. Prod. J. 58, 56–72.
Statistics Canada, 2005. Solid Waste in Canada, Human Activity and the Environment (Ottawa, ON, Canada).
Swiss Centre for Life Cycle Inventories, 2013. Ecoinvent Database (Dübendorf, CH).
Wang, X., Padgett, J., De la Cruz, F., Barlaz, M., 2011. Wood biodegradation in laboratory-scale landfills. Environ. Sci. Technol. 45, 6864–6871.
Werner, F., Althaus, H.-J., Künniger, T., Richter, K., Jungbluth, N., 2007. Life Cycle Inventories of Wood as Fuel and Construction Material, Ecoinvent. Swiss Centre for Life Cycle Inventories, Dübendorf, CH report no9.
Ximenes, F., Gardner, W., Cowie, A., 2008. The decomposition of wood products in landfills in Sydney, Australia. Waste Manag. 28, 2344–2354.

Literature cited

Hydro-Québec, 2012. Faits sur l'électricité d'Hydro-Québec. Approvisionnement énergétique et émissions atmosphériques. Available at:. In: Hydro-Québec (Ed.) http://www.hydroquebec.com/developpement-durable/pdf/approvisionnements_energetiques_et_emissions_atmospheriques_d_hydro_quebec_2012.pdf.
Itten, R., Frischknecht, R., Stucki, M., 2013. Life Cycle Inventories of Electricity Mixes and Grid. ESU-services, Uster, Switzerland, p. 220.
National Research Council, 2010. Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-duty Vehicles. The National Academies Press.

Please cite this article in press as: Cobut, A., et al., The environmental footprint of interior wood doors in non-residential buildings – part 1: life cycle assessment, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.04.079