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Reducing the environmental footprint of interior wood doors in non-residential buildings – part 2: ecodesign

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ABSTRACT

Ecodesign is a concept that emerged few decades ago as a response to the larger concept of sustainable development. Multiple tools exist to address ecodesign. Life Cycle Assessment, a comprehensive, robust and recognized evaluation tool, enables to identify the product environmental profile. Based on previous LCA results on interior wood doors, this paper aims at proposing an ecodesign strategy based on the generation and evaluation of alternative scenarios. The three selected targets for environmental improvement are particleboard components, transportation and end-of-life. For the particleboard manufacturing, the use of adhesives based on bio-sourced resources was not very conclusive, except for the use of pine tannins in panel manufacture that showed promising results. Concerning transportation issues, switching from road to rail transportation, as well as having a local supplier, decreased the overall environmental impact of the door. The most notable alternative was the end-of-life recycling scenario. The reutilization of the door core in the door manufacturing process proved a great benefit due to the avoidance of new raw materials production. Developing services around door recovery and remanufacturing seems promising in reducing doors environmental impacts. This scenario would be readily viable and realistic.

1. Introduction

1.1. Ecodesign

The concept of sustainable development has been first introduced in *Our common future* report also known as the Brundtland report in 1987 where the sustainable development is defined as a development that satisfies the needs today without compromising the possibility of future generations to fulfill their needs (World Commission on Environment and Development, 1987). This definition of sustainable development has been a precursor and influenced the current process of economic and technological development. It is an important step in the course of raising the issue of environmental protection with the promotion of the concept of *producing more with less*. Concerning, the actors involved in industrial development, it has been demonstrated that industries must acquire knowledge and capacity to assume their responsibilities in the development of sustainable production systems. In parallel, governments have the responsibility of creating those socio-economic conditions allowing companies to assume their responsibilities while remaining competitive (Guidice et al., 2006).

Ecodesign, also known as Design for Environment (DfE), Green Design (GD) or Environmentally Conscious Design (ECD), can be defined as the interpretation of sustainable development in the context of industrial processes and products design (Guidice et al., 2006). The main characteristic of this approach is the objective to minimize the impacts of products on the environment early in the design phase. 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 providing direction to product development, pursuing 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 imposed itself.

DfE implementation consists in three consecutive phases: scoping, data gathering and data translation. Firstly, a target must be defined and possible alternatives identified. Secondly, a

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significant amount of environmental data must be collected, analyzed and interpreted. Finally, the previous results must be translated into tools, which go from simple guidelines and design procedures to more sophisticated software systems (Guidice et al., 2006). Other authors consider the implementation of environmental issues in product development in four levels (Brezet, 1998; Stevels, 1999). The first ecodesign level would be product improvement, easily handled by designers and engineers. The second level is product redesign, also manageable for both designers and engineers. The third level of ecodesign is called function innovation and can be handled by managers. The last level of ecodesign implementation in a company is system innovation. Decisions at this level are mostly made by governments.

Our research project can be situated in the second phase of ecodesign implementation. It proposes alternatives to an original product system and interpretation of environmental impacts scores with the support of the Life Cycle Assessment methodology.

1.2. Life Cycle Assessment role in ecodesign

A good understanding of the main environmental problems caused by the product system during its entire life cycle is essential to ecodesign. A wide panel of specific tools both qualitative and quantitative is available to help throughout the process of environmental profiling. Life Cycle Assessment (LCA) can be cited among the quantitative tools. LCA is recognized as an efficient method to determine environmental impacts but it requires a great amount of effort. While the United Nation Environment Program (UNEP) report on ecodesign recommends the use of LCA for the entire system if the environmental impacts of the product system have not been yet investigated, others recommend a systematic use of LCA in the ecodesign process (Brezet and Van Hemel, 1997). Only a systemic vision of the product over its entire life cycle can, in fact, ensure that the design activity not only identifies the environmental criticalities but also enables effectively avoiding impacts transfer (Guidice et al., 2006).

LCA focuses on the environmental impacts of the system but the ecodesign decision may be taken considering in parallel other aspects. In addition to economical performance and technical feasibility, costs and social implications can be assessed using life cycle thinking related tools such as Life Cycle Costing (LCC) and social LCA (sLCA) (Jolliet et al., 2010).

1.3. Environmental studies on wooden doors

Architectural wooden doors are widely specified in non-residential buildings in North America (Drouin et al., 2012). However, as far as doors are concerned, the number of studies about ecological performances or development is very limited. Only one scientific study about doors has been published. Knight et al. (2005) made a comparative life cycle inventory (LCI) of two types of doors, a steel door and a wooden door. However, they made a partial LCI including only the cradle-to-gate energy use and environmental emissions. Besides, in their report, O'Connor et al. (2009) analyzed the former study and express that even with a full cradle-to-gate LCI, conclusions of the Knight et al. study may not change because of the major difference of magnitude in their respective environmental performance for both type of doors. The steel door creates 40 times more waste, causes 27 times more greenhouse gas emission and consumes 22 times more energy than its wooden counterpart. 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 and does not include an environmental impact assessment study, whereas our study is a cradle-to-grave LCA. As for ecodesign, no scientific studies have been made for interior doors yet. The current work intends to provide a new perspective to such issues.

Eventually, interior wooden doors might be chosen primarily by cost and secondarily by their environmental footprint. Many aspects can make a wooden door less environmentally friendly like the provenance of its wood, core materials, bonding materials and its coating. In this context, evaluating and improving its environmental footprint are relevant.

1.4. Sustainable building program implications

As sustainable building programs keep growing in importance, it is essential to ensure that appearance wood products are truly environmentally responsible. LCA is rightly more and more viewed as essential in these programs. Besides, the use of Environmental Product Declaration (EPD) for building products is becoming a requirement in most sustainable building programs, encouraging building product manufacturers to engage in this process. Even though EPD permits to have a transparent view of a product environmental footprint, it does not ensure a good environmental performance. To this end, ecodesign of interior appearance wood product is a necessary step to consider.

1.5. Research aim and scope

This study explores alternative scenarios of ecodesign stemmed from previous LCA results. This study aims at expanding the current knowledge on environmental impacts and ecodesign opportunities associated with appearance wood products.

2. Ecodesign methodology

2.1. Comparative LCA

The current research has been carried out following recommendations of the ISO 14040 series (ISO, 2006a,b). Guidice et al. (2006) explain that for the analysis and improvement of a product-system or the comparison between different systems, LCA can help in determining the environmental criticalities of the solution under examination. Same applications are presented in the ISO 14000 series (ISO, 2006a), such as, identifying opportunities to improve the environmental performance of products at various points in their life cycle, and product or process design or redesign. Therefore, this study is dedicated to the application of LCA results. Those results provide useful information to elaborate ecodesign strategies in the context of interior wooden doors for non-residential applications.

2.1.1. Product system

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 province of Quebec, Canada. A complete description of the product system can be found in Cobut et al. (in press, corrected proof), as well as its functional unit and system boundaries.

2.1.2. Allocation procedure

Allocations have been mostly used in this ecodesign work for the creation of alternative scenarios. Most of the raw materials used in alternative scenarios were co-products of other main manufacturing processes. When using a co-product from a manufacturing process, it has been decided to refer to the allocation factors presented in their respective LCI studies or to existing

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allocation factors from the *Ecoinvent* database (Swiss Centre for Life Cycle Inventories, 2013). When nothing could be found, mass allocation has been applied.

2.1.3. Data sourcing and quality

The primary data for the baseline model, mostly obtained from the manufacturer, was representative of the current technologies and materials used by this company. When primary data was not available, unit processes were selected from the *ecoinvent* database, the most comprehensive LCI database currently available. Most unit processes have been adapted to a Quebec or North-American context, since *Ecoinvent* is mostly based on European processes and data. As transportation was a major contributor to the baseline model environmental impacts, a sensitivity analysis was performed concerning truck loading (±25% of actual loading 17,56 tons) and life cycle transportation distances (±25%). Results show little sensitivity from these parameters and the main conclusions were maintained.

The main sources of input data in the ecodesign step are the *ecoinvent* database, modified or created *ecoinvent* unit processes based on scientific literature. To satisfy the functional unit, when the alternatives concerned a door component (e.g. wooden board), the choice of one panel composition over another, was done according to their mechanical performance as stated in the industrial standard on flush doors from the *Window & Door Manufacturers Association* (WDMA) (WDMA, 2006). As a matter of fact, the majority of studies found in the scientific literature were on technologies in development. Therefore, the lack of actual process data and, when applicable, the use of approximations concerning water and energy consumption for alternative scenarios may bring further uncertainties on the output results. According to Crawford (2011), associated uncertainties typically range between 5% and 20%.

Finally, the baseline model environmental impacts uncertainty has been determined in SimaPro using Monte Carlo analysis with 1000 iterations. The results on a damage level are presented in Table 1. Coefficients of variation for damage category scores vary from 11.9% to 16.1%.

2.1.4. Life cycle impact assessment (LCIA)

As in the LCA of Cobut et al. (in press, corrected proof), *IMPACT 2002+* was chosen (Humbert et al., 2005) as main impact assessment methodology and *ReCiPe* (Goedkoop et al., 2012) as supportive methodology for validation purpose. A brief description of their respective impact categories is presented in Table 2.

2.2. Life cycle inventory for alternative scenarios (LCI)

The purpose of a life cycle inventory 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 the international level. However, the data is much more detailed in western European contexts than in others. LCI data for the original system are detailed in Cobut et al. (in press, corrected proof).

In view of the LCA results (Cobut et al., in press, corrected proof), the trails for environmental impacts reduction has already been established. Thereby, it has been possible to draw eight ecodesign scenarios from the first observations. All scenarios are summarized in Table 3. In cases where scientific literature has been involved, the references are noted. Scenarios 1 to 4 involve only the first life cycle stage. Scenarios 5 and 6 propose solutions from the shipping stage. Finally, scenario 7 and scenario 8 were created around the end-of-life impacts.

2.2.1. Alternatives in particleboard composition

From previous work (Cobut et al., in press, corrected proof), the particleboard stood up from the other door components for its environmental impacts. The UF resin, used as a binder in particleboards, was seen as the main source of impacts. This conclusion led the path to considering alternative chemicals in the adhesives used for the particleboard manufacturing. Several studies found in the scientific literature reported the use of natural adhesives or other synthetic adhesives to prevent the formaldehyde degasing of traditional synthetic resins. The different adhesives scenarios have been chosen because they reflect recent developments in the adhesives research and development field (Pizzi, 2013). Scenario 1 and scenario 2 depicts the use of condensed tannins in the composition of adhesives employed in particleboard manufacture, whereas scenario 3 highlights the use of vegetal proteins as wood boards adhesives (Table 3).

Another approach was to switch raw materials such as wood residues to agricultural fibers (Scenario 4 in Table 3). This choice was mainly supported by the fact that the door manufacturer already used such boards as "green" core in their products.

Since scenarios 1 to 4 integrate mostly multi-output processes, economic or mass allocations are involved. More details are explained in the following sections. According to Huijbregts et al. (2003), allocations can also be a source of uncertainty. A sensitivity analysis has only been carried out for allocations assumptions on grape pomace, *ecoinvent* processes having predetermined allocation factor.

2.2.1.1. Adhesives based on natural resources, scenarios 1 to 3. Scenario 1 is founded on Valenzuela et al. (2012) research about pine tannin-bonded particleboard and MDF. In the study framework, pine bark tannin adhesives have been used at an industrial scale, as described in Valenzuela's study, for the manufacture of particleboards and some MDF in an existing plant in Chile from 1993 to 2002. In the modified process from ecoinvent database, the actual resin was replaced by the trialed composition described in this paper, which was composed of pine tannin extracts and hexamine. The exact composition can be seen in the reference (Valenzuela et al., 2012). The choice has been made according to

Table 1
Uncertainty results from Monte Carlo Analysis in SimaPro for the base model using IMPACT 2002+ as the output methodology (1000 iterations). HH: Human Health, EQ: Ecosystem Quality, CC: Climate Change, and R: Resources.

Damage category	Unit	Mean	Standard deviation	Coefficient of variation (%)
HH	DALY	29.7	3.71	12.5
EQ	PDF m^2 yr	15.4	2.37	15.4
CC	kg CO_2 eq	$2{,}78 \cdot 10^{-5}$	$3{,}31 \cdot 10^{-6}$	11.9
R	MJ primary	647	104	16.1

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Table 2
Description of *IMPACT 2002+* 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	
	Ionizing 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 a certain amount of m^2 during a certain amount of year. This unit represents the fraction of species disappeared on 1 m^2 of earth surface during one year.
[c] MJ primary: Mega Joule primary. The unit measured 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
Presentation of proposed ecodesign alternatives and their references.

Life cycle stage concerned	Original scenario	Scenario	Enhanced scenarios	Reference
Raw materials	UF resin as adhesive in PB fabrication	1	Pine tannin resin as adhesive in PB fabrication	(Sealy-Fisher and Pizzi, 1992; Valenzuela et al., 2012)
		2	Grape pomace tannin resin as adhesive in PB fabrication	(Ping et al., 2011a; Ping et al., 2011b)
		3	Soy Protein resin as adhesive in PB fabrication	(Khosravi et al., 2010; Wang et al., 2004)
	Wood industrial residues in PB fabrication	4	Straw fibers in PB fabrication	(Mo et al., 2003)
Transportation	Road	5	Freight	
	Long sourcing distance	6	Locally sourced HDF	
End-of-life	Landfilling	7	Recycling the door core assembly	
	Landfilling	8	Energy recovery	

mechanical tests results of different boards. No further details on durability of this kind of particleboard were given in the article. Nonetheless, relying on mechanical properties to choose the best board composition and therefore comply with the WDMA standard (WDMA, 2006) has permitted to ensure basic requirements for the functional unit. The manufacturing process of pine tannins has been created using data from a Sealy-Fisher and Pizzi study (Sealy-Fisher and Pizzi, 1992) and the ecoinvent report on LCI of chemicals for missing data making hypothesis on energy consumption, water consumption or transportation employed in chemicals production (Althaus et al., 2007). In *ecoinvent*, the economic allocation factor for pine bark is zero. Softwood bark is considered as a waste.

Scenario 2 has been based on Ping et al. (2011b) research that aimed at taking advantage of the underutilized grape pomace, a waste from wine production. They used grape pomace to extracts tannins as well. With the same procedure as scenario 1, the adhesive composition was selected according to the board test performance. The production process of grape pomace tannin was created combining LCI data on wine production (Gonzalez et al., 2006; Point, 2008) and tannin extraction from grape pomace (Ping et al., 2011a). The same hypotheses have been made about energy, water consumption and transportation for tannin extraction as in scenario 1 (Althaus et al., 2007). Allocation factor for grape pomace are based on mass. Environmental impacts are allocated to wine production at 74.8% and to grape pomace at 25.2%.

Scenario 3 is based on Khosravi et al. work (2010) dealing with particleboards bonded with soy protein isolates. The adhesive unit process in SimaPro has been modeled using the ecoinvent unit process soybean meal as starting point for the production of the soy protein. The data have been sourced from the Wang H et al. study (2004) on soybean protein production. The manufacture of soybean protein bonded particleboard has been modeled with the same protocol as previous scenarios (1 and 2), meaning that the composition was determined by the mechanical test results. In *ecoinvent*, soybean meal process used to produce soy protein has an economic allocation factor of 65.5% against 34.5% for soybean oil process. The multi-output process is soybean production.

2.2.1.2. Agricultural fibers, scenario 4. As mentioned before, this scenario has been made in accordance with existent manufacturing choice from the door producer. Wood particles have been replaced in this case by wheat straw particles. Process inputs have been selected regarding several scientific publications both articles and reports. The majority of scientific papers do not indicate the amount of wheat straw needed to realize one panel of a specific size and density. However, as an approximation, data from Lam et al. (2008) and a formula for estimating wood requirements in producing non-veneer panel products has been used (Briggs, 1994). Publications on particleboard from wheat straw have been searched for quantitative data on adhesives and chemical pretreatment requirements for panel processing (Mo et al., 2003). In the ecoinvent unit process, changes have been only made on panel composition (chemicals and raw materials). Energy and waste flows for panel production were kept the same. Economic allocation factor for wheat straw is 7.5% against 92.5% for wheat grains in *ecoinvent*.

2.2.2. Alternatives in transportation

The original system impacts were also largely influenced by transportation. The majority of material flows were obtained by trucking. Only one raw material came to the plant by train. Some raw materials come from the province, some come from the United-States. The shipping to the building site was also done by truck to the nearby province of Ontario. Since the mean of transportation preferred in this case study was truckload, it has been decided to switch in favor of railways. Railways having a lowest environmental footprint than road transportation (Aranda Usón et al., 2011; Facanha and Horvath, 2006). This section includes scenario 5 and 6 that are described hereby. As in the first part (Cobut et al., in press, corrected proof), Transportation processes are based on both *ecoinvent v2.2* for rail freight and a National Research Council report (2010) for road transportation. The latter report has been used to approximate the road fleet in North America. The created process simulates a 53 feet long truck with an average truckload of 17.56 tons and a maximum of 25 tons, including no empty returns. Rail transportation was modeled using a US diesel train unit process from the *ecoinvent* database.

2.2.2.1. Substitution of road transportation by freight transportation, scenario 5. In scenario 5, all original road transportation has been substituted by rail transportation. This scenario was intended to assess how much replacing a 53 ft long truck with a diesel freight train could diminish environmental impacts.

2.2.2.2. Locally sourced raw materials, scenario 6. With scenario 6, the intention was to analyze the effect of buying products from nearer specialized manufacturers. With this aim in mind, the product found to be brought from the farthest location has been considered. The raw material collecting the maximum of km from its original plant to the door manufacturer is the fiberboard with 3900 km. However, it has been possible to find a potential manufacturer of HDF in the province of Quebec. The nearest manufacturer of HDF eligible for this scenario is located in Quebec at around 480 km. In the original scenario, a major part of the distance was covered with freight, while in the new scenario distance is covered with road transportation.

2.2.3. Alternative to landfill, scenario 7

The end-of-life is one of the most contributive life cycle stages for the door system. These impacts are related to both transportation and landfilling of the door. Moreover, as landfilling is not a long-term solution for building waste, it has been decided to create a scenario that would divert the door from landfill site. On one hand, scenario 7 proposes the reutilization of the door core assembly in the original manufacturing line as in a closed-loop scenario. On the other hand, scenario 8 proposes to recover the door for heat production in place of fossil fuel utilization.

Scenario 7 comprises all steps needed for the reutilization of the door core. The first step consists in transporting the door from the building site back to the door manufacturer. Then, the door is brought to a sanding machine, where the two face assemblies are removed. The remaining core assembly is then brought to the final assembly line, glued and pressed with two new faces. Finally, the new door is trimmed and then brought to the finishing line. The product goes through the packaging stage once again and is shipped and installed in another building site. At the end of its second life, the door is landfilled. In this scenario, two life cycles are considered. The door needs to complete its first life cycle so it becomes possible to use it once again.

Scenario 8 models the energetic valorization of the door. Chips made out of the door are burned in a furnace to replace light fuel oil. In *ecoinvent 2.2*, the unit process used does not reflect accurately wood composite burning that needs high temperature and high filtering capacity. Actually, it simulates virgin wood burning. Nevertheless, since this unit process was readily available, it has been considered as an approximation. However, it surely represents a supplementary source of uncertainty in the output results. Burning the door was assumed to generate approximately 888,2 MJ according to the gross heating value based on its size, composition and moisture content.

3. Results & discussion

Before examining the results, it should be mentioned that the alternatives scenarios are discussed at the damage level for the purpose of comprehension. In graphs, each alternative scenario are presented as a percentage of baseline scenario overall life cycle damage score. In some sections, specific stage impacts are given alongside overall damage score to clarify the discussion.

3.1. Alternatives in particleboard composition

3.1.1. Adhesives based on natural resources, scenario 1 to 3

Fig. 1 shows the results of the first scenarios on natural adhesives. Scenario 1 helps reducing environmental impacts of the system in each of the four damage categories. The most important reductions are observed for the climate change damage and resources categories with 30% and 37% respectively. The lesser important reductions are observed for human health and

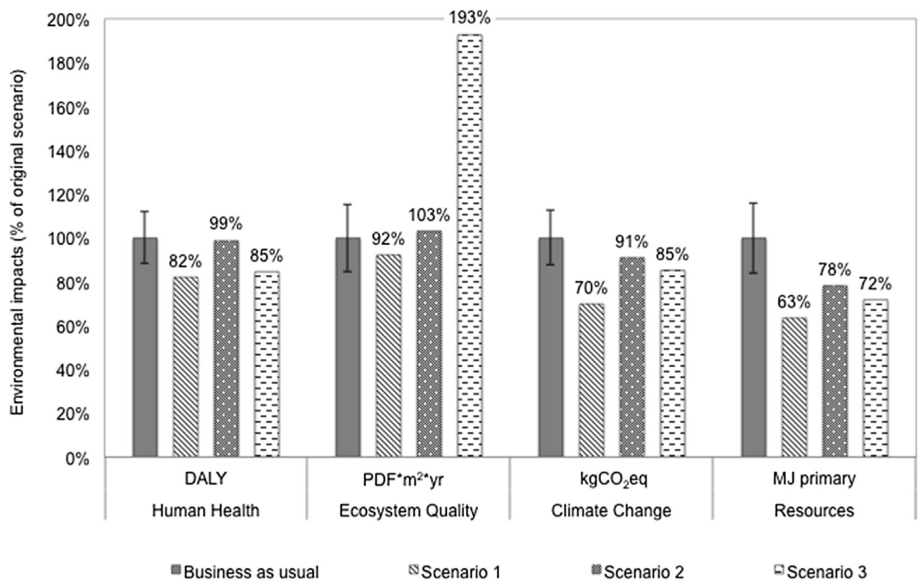

Fig. 1. Environmental impacts expressed for natural adhesives (scenarios 1, 2 & 3) in % of business as usual (BAU) scenario. Results presented for each *IMPACT 2002+* damage category. Scenario 1: pine tannin adhesive; Scenario 2: grape tannin adhesive; Scenario 3: soy based adhesive.

ecosystem quality with a decrease of total impacts of 18% and 8% respectively. Scenario 2 shows a clear difference in environmental impacts for climate change and resource damages. For human health and ecosystem quality, the impacts appear to remain the same when compared to but business as usual (BAU) scenario. For scenario 3, a decrease in environmental impacts is obtained for three following damage categories: human health, climate change and resources. However, the impacts on ecosystem quality are nearly doubled at 193%.

Scenario 1, which uses pine tannin in particleboard bonding, provides the best impact reduction results. It may be explained by the fact that bark is already a by-product of wood-products processes in Ecoinvent. Moreover, grape pomace tannins in adhesive production did not really improve the environmental impact of the system in human health and ecosystem quality maybe because grape crops consume fertilizers and pesticides for soil management. By contrast, the last scenario concerning the utilization of soy protein isolates as a substitute adhesive helps diminishing impacts on three damage categories but nearly doubles the impacts on ecosystem quality. From the analysis of a network view for ecosystem quality, the source of impacts is mainly related to the cultivation of soybean, the use of machinery and fertilizers such as diammonium phosphate, potassium chloride and many others. In this study, the unit process chosen for the production of soy protein isolates is based on US production practices. Actually, three producing countries are available in the Ecoinvent database: Switzerland, Brazil and the United States. The United States was chosen since they are the largest world producer of soybean (39.4% of the world production), followed by Brazil (23.9%) and Switzerland (18.2%). In Switzerland, the use of N-fertilizer and machine and the emissions of nitrate are higher than in Brazil and the US. The land occupation in Brazil is lower because two harvests per year are possible. An important difference between the Brazilian production on the one hand and the US and Swiss productions on the other hand is the emission of CO_2 from land transformation caused by deforestation of rainforests. The higher value in the emission of NMVOC in Brazil is also caused by deforestation (Jungbluth et al., 2007).

3.1.2. Agricultural fibers, scenario 4

The results obtained for this scenario are compared to the BAU scenario scores in Fig. 2. The environmental impacts related to the production of straw-based particleboard are clearly above the scores for the BAU scenario, and that in every damage category. The damages on human health, climate change and resources are more than doubled and the damages on ecosystem quality are more than tripled. A sensitivity analysis has been carried out for this scenario given the large differences. The chemical pre-treatment of wheat-straw with a 3% bleach solution is undeniably linked to these large scores. In related publication (Mo et al., 2003), the straw was mixed in a volume ratio 1:10 with the bleach solution. Considering the volume of straw needed to produce a low-density particleboard for our system, it is easy to realize that a high volume of solution is needed for bleaching the raw material. Straw, that is a by-product of wheat production, has non-negligible impacts on the ecosystem quality as observed for soy production but is still inferior to the impacts of bleach usage.

3.1.3. Discussion on particleboard eco-alternatives

The propositions defined to counter particleboard impacts yielded interesting results. Scenarios on natural adhesives alternative have shown that pine tannin was an option worth considering because of its environmental impact benefits. The other alternatives scenarios yielded mixed results. On one hand, the grape pomace tannin based adhesive did not show significant environmental benefits on the door, on the other hand, the soy-based adhesive yielded good results except for ecosystem quality where it doubled the impacts. Finally, scenario 4 on the use of wheat straw showed that straw particles pre-treatment is a major contributor to environment damage. However, the pre-treatment is not something that can be dismissed because of its necessity for improving the adhesion between the straw particles and the resin. Considering that the uncertainty results from the baseline model (Table 1) gave coefficients of variation ranging from 11.9% to 16.1% for damage categories scores, it is visible that the use of grape tannin adhesive falls into the range of impacts variations except for resources score that is under 16.1%. Soy based adhesive performs better than grape tannin except for the ecosystem quality score

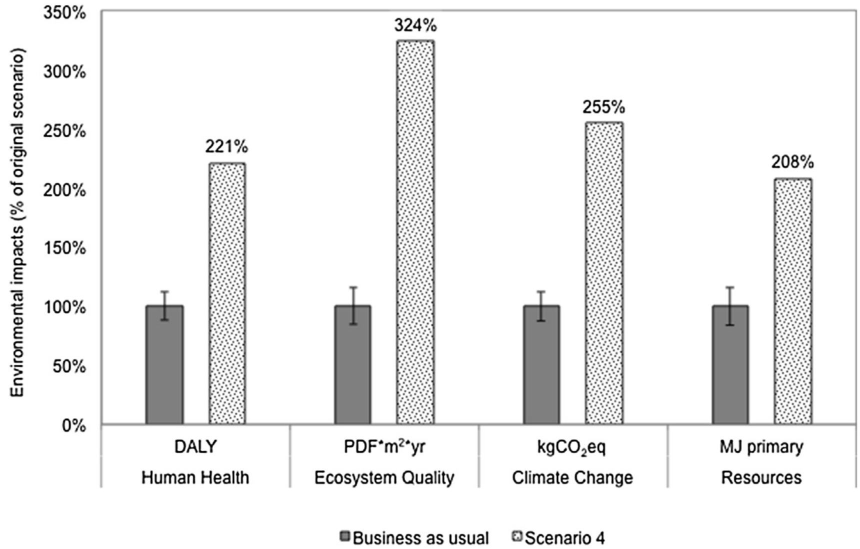

Fig. 2. Environmental impacts expressed for the agricultural raw material (scenario 4) in % of BAU scenario. Results presented for each IMPACT 2002+ damage category. Scenario 4: straw fibers.

when considering impacts variation. Pine bark tannin scenario demonstrates the biggest benefits beyond impacts variation except for ecosystem quality. Pine bark and grape tannin adhesives seem to have a neutral influence on ecosystem quality impacts considering damage score variations. Overall, scenario 1 appears to be the most promising of particleboard related scenarios.

3.2. Alternatives in transportation

3.2.1. Substitution of road transportation by rail freight transportation, scenario 5

The scores for the four damage categories for the transportation alternative scenario are displayed in Fig. 3. Road transportation is found both at shipping and raw materials stages. Considering the LCA results, total transportation contribution for the door life cycle is equal to 32.3% for human health, 15.6% for ecosystem quality, 23.9% for climate change and 17.7% for resources. With rail freight, the total impact decreases by 6% in the human health category, 9% for ecosystem quality, 9% for climate change and 7% for resource damages. These numbers may appear small because they are accounted across the whole life cycle of the door. They do represent a decrease of transportation related environmental impacts of respectively around 16% for human health, 56% for ecosystem quality, 38% for climate change and 44% for resources.

3.2.2. Locally sourced raw materials, scenario 6

Fig. 4 presents the score of scenario 6, the scenario considering sourcing local materials instead of far-away materials, for the four

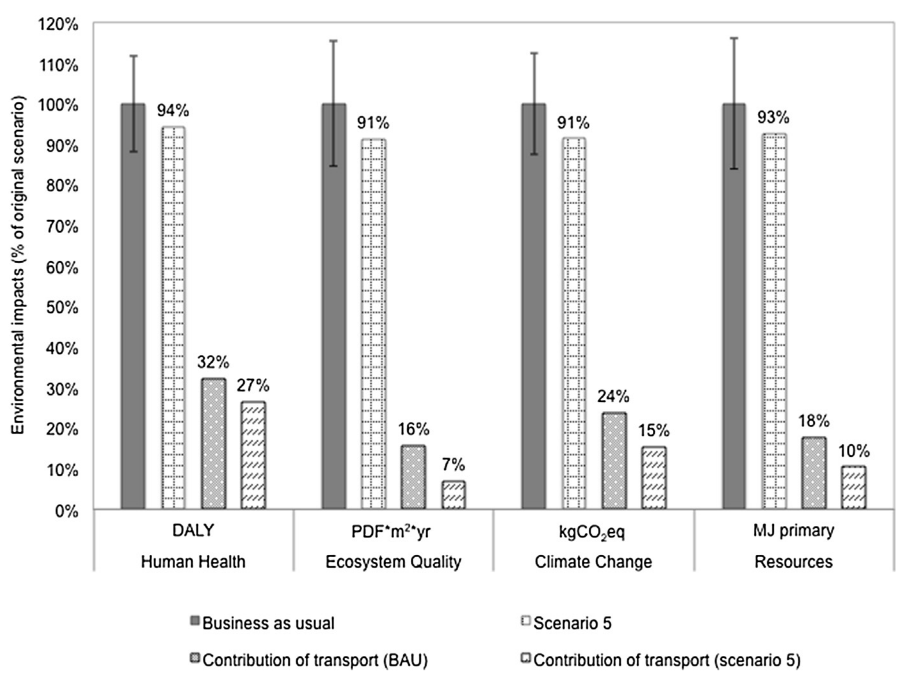

Fig. 3. Environmental impacts expressed for rail freight alternative (scenario 5) in % of BAU scenario. Results presented for each IMPACT 2002+ damage category. Contributions of transport to the life cycle damage score are shown for a focused comparison between BAU scenario and scenario 5.

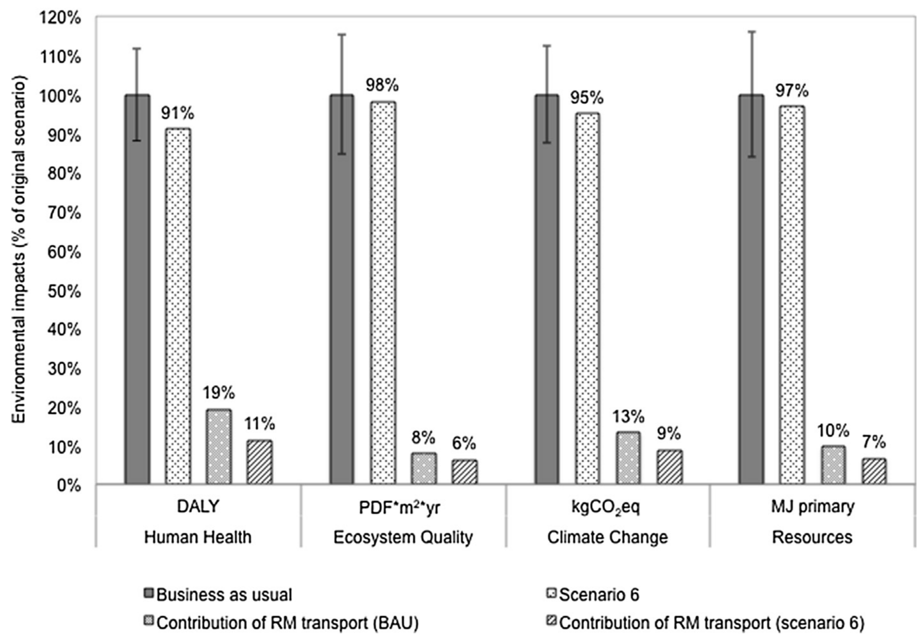

Fig. 4. Environmental impacts expressed for locally sourced HDF (scenario 6) in % of BAU scenario. Results presented for each IMPACT 2002+ damage category. Contributions of raw material transport to the life cycle damage score are shown for a focused comparison between BAU scenario and scenario 6. RM: Raw Materials.

damage categories. Similarly to scenario 5, reductions in environmental impacts on the four damage category appear weak, even weaker. The most important decrease is for the human health damage with 9%. For the three other categories contributions to damages are reduced by 2% for ecosystem quality, 5% for climate change and 3% for resources damages. Zooming on the benefits at the raw materials transportation, the HDF bought from a manufacturer in the same province makes a difference. The impacts from raw materials transportation drop by circa 42%, 25%, 31% and 30% on human health, ecosystem quality, climate change and resources respectively, although raw materials transportation is not a large contributor over the whole life cycle of the doors.

3.2.3. Discussion of transportation alternatives

Replacing road transports with rail freight has proven to be positive but yet mild on reducing transportation related impacts when considering damage scores variations of the baseline model (Table 1). Scenario 6 that is about switching to locally available products provides also a positive but weak feedback, meaning that impacts related to transports have decreased by at least a quarter but this component is a small contributor to overall impact. The maximum score reduction in scenario 6 was observed for damages on human health. At midpoint indicator level, the indicator respiratory inorganics showed the most important diminution. It is known to be related to road transportation or fossil fuels consumption in *IMPACT 2002+* (Humbert et al., 2005). However, Humbert et al. (2005) explain that the difference in respiratory organics impacts, when comparing two scenarios, should be more than 30% to call it significant. The same goes for energy and carbon dioxide emissions that should be at least different by 10% for two compared scenarios, which is not the case for either alternative.

3.3. Alternatives to landfill

3.3.1. Remanufacturing of the door with core reutilization, scenario 7

The differences in environmental impacts for the manufacturing of two doors with virgin cores as compared to that of two doors reusing the same core assembly are depicted in Fig. 5. The typical service life of the door is 40 years according to the manufacturer but the door core maintains its integrity because of its location in the product. Extending the life of the core assembly has strong beneficial impacts on the system. The damages on ecosystem quality and resources were decreased by 29% and 28% respectively, while the scores for human health and climate change have been reduced by 26%. With scenario 7, the transportation for all core assembly components is avoided, as well as their raw materials extraction and processing although transportation costs are incurred for recovering the used cores. For example, producing wood products does have an impact on ecosystem quality. Avoiding the manufacturing of additional wood based products diminishes damages to ecosystem quality. Moreover, the core assembly has the largest weight percentage, so its impact on transportation, expressed in tons per kilometer, can be quite important, in spite of impact added by recovery transportation of used doors. Thus, by refraining its component supply, overall benefits appear on the environmental footprint.

3.3.1.1. Number of recycling cycles. Given the previous results, it has been decided to extend the number of core reutilizations in the door manufacturing process. The core assembly should not be subject to moisture or any other exterior elements since it is an indoor product. Also, the core is tightly protected by PVAc adhesives and two face assemblies. Finally, because the core has no important mechanical purpose, except maintaining all hardware in place, its lifespan could easily be extended. The number of reutilizations has been set to a maximum of 4 to uncover any trend.

Fig. 6 shows the results obtained for the simulation of numerous reutilizations of the core assembly. The graphic represents the evolution of environmental impact due to core reutilization in the four damage categories of *IMPACT 2002+*. Using the core for a third door manufacturing reduces the impacts by 25%–30% depending on the damage category, results that are verified in the above observations. Reutilizing the core assembly a second time, diminished the environmental score by 35%–40% when compared to the manufacturing of three doors with primary cores. When the door

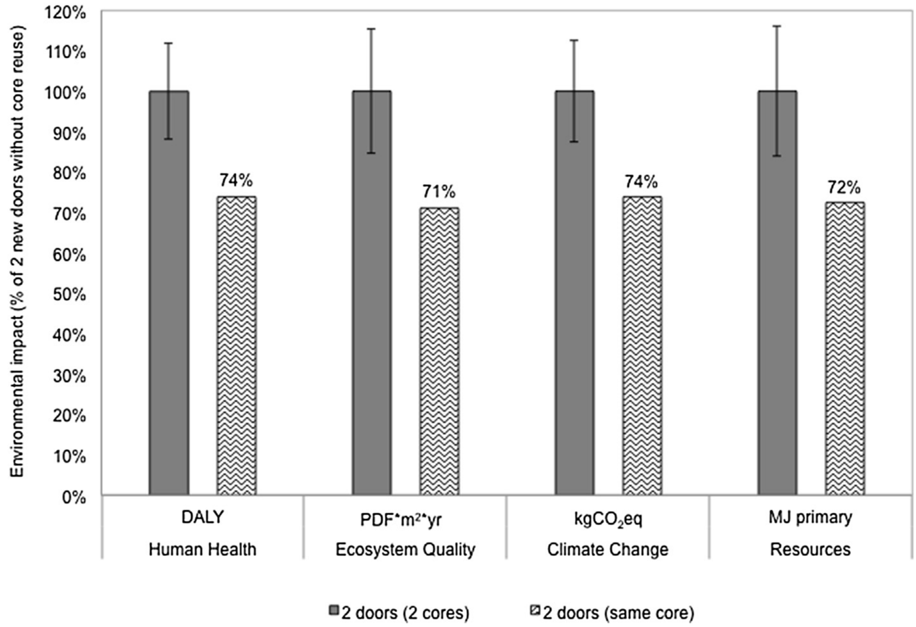

Fig. 5. Environmental impacts expressed for remanufacturing (scenario 7) in % of BAU scenario. Results presented for each IMPACT 2002+ damage category.

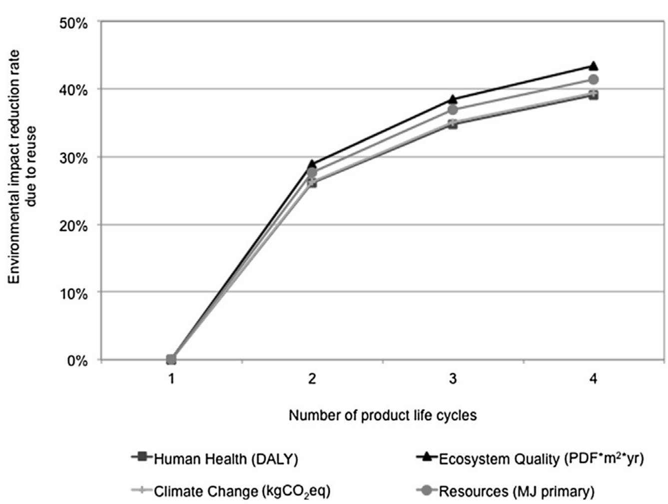

Fig. 6. Evolution of the environmental impact reduction due to core reutilization in the remanufacturing process. The evolution is expressed for the four damage categories of IMPACT 2002+.

core is used in a third manufacturing cycle, the environmental benefits vary from less than 40%–45%. The values for each damage category show the same reduction pattern, meaning that values for ecosystem quality are always those with the largest impact reductions, followed by the scores for resources. Lastly, the scores for human health and climate change follow the same trend. The ecosystem quality category has the highest reduction rate due to saving on wood materials in the manufacturing of the core assembly. As was seen previously the production of wood products have an impact on ecosystem quality, more specifically through the land occupation midpoint category. Resources would show the second highest diminution rate because of savings in road transportation and raw materials extraction and transformation.

3.3.2. Energy recovery, scenario 8

Results for scenario 8 are presented in Fig. 7. Whereas energy recovery for substituting light fuel oil in heat production seems beneficial for climate change and resources damage categories with an impact reduction 232% and 161% respectively, the contrary is observed for damage categories human health and ecosystem quality with an impact increase of 91% and 75% respectively. Emissions from the burning process overcome the benefits of avoiding light fuel oil burning for these two damage categories. Using an approximate unit process makes it difficult to prospect on how much damage could be prevented on human health and ecosystem quality by burning particleboard chips in an appropriate furnace. It also requires that characterization factors are available for those specific emissions. In *ecoinvent 2.2*, resulting ashes are disposed in landfills whose impacts contribute to ecosystem quality. However, chemical composition of pure wood ashes and particleboard ashes burned in high efficiency furnace may differ (Rector et al., 2013), as may their environmental impacts, bringing uncertainty to the results.

3.3.3. Discussion on end-of-life alternatives

Using a recycled core as raw material allows avoiding 25%–30% of door life cycle environmental impacts. Likewise, it is interesting to notice that more impacts could be avoided by reutilizing the core more than once. With this scenario, the environmental footprint of the door benefits from important reductions in all damage categories, especially ecosystem quality and resources. However, environmental benefits of scenario 8 are neither great nor poor. A significant decrease is observed for climate change and resources damages, but this is balanced by a significant increase in damages on human health and ecosystem quality. Definitely, a more accurate modeling of the burning processes for particleboard chips would have permitted a deeper interpretation.

4. Recommendations

On the basis of results from proposed ecodesign scenarios, it is possible to make several recommendations. In this section, the legitimacy of natural products to create green products will be discussed. Then, the issue of transportation will be addressed. Finally, regarding the recycling scenario results, ideas about what can be done will be developed.

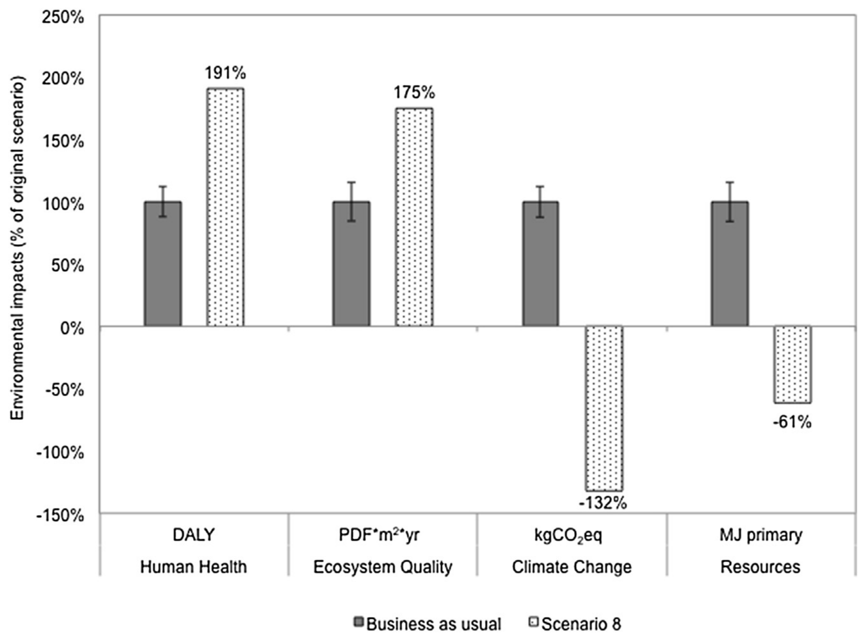

Fig. 7. Environmental impacts expressed for energy recovery in place of fossil fuel for heat production (scenario 8) in % of BAU scenario. Results presented for each IMPACT 2002+ damage category.

4.1. Bioproducts in ecodesign

In ecodesign scenarios 1 to 3, the substitution of synthetic resin in particleboard production by bio-based resins was discussed. In scenario 4, the replacement of wood particles by wheat straw particles was addressed. In common sense, the notion of "bio" is often mixed with "natural" and automatically associated to environmentally friendly or healthy. However, a biomaterial does not possess necessarily those two properties and caution should be used. To be able to judge in a relevant manner on materials environmental footprint, the use of LCA is necessary. The analysis must be performed over the entire life cycle to prevent environmental impacts transfer and to look at each aspect of the product life cycle. The ecodesign results demonstrate the need to use such method to be able to decide on products environmental efficiency. In fact, the use of tannin-based resins or soy-based resins seems appealing from the standpoint of the wood panel industry. Our research, however, shows that only pine tannins would reduce the environmental impacts in every damage category. Grape pomace tannins and soy protein isolates have a significant impact on ecosystem quality because of the production of grapes and soybeans respectively. For wheat-straw panel production, the source of impact seems to come from the chemical pre-treatment needed for particles washing, thus surpassing the environmental impacts of the conventional wooden particleboard. Therefore, the idea to replace wood particles to save trees by wheat straw particles that are a by-product of wheat production seems legitimate in the beginning but their physical, chemical and process characteristics have to be taken into account to obtain equivalent functionalities and the whole picture must be analyzed to avoid impacts transfer. Performing complete LCA often yields counter intuitive results thus preventing to rush into solutions of ecodesign that are not.

Various studies support the theory that the use of biomaterials has to be revisited to evaluate their true contribution. Biofuels from food crops are one of the most debated *green* technologies. The monoculture of crops, often corn, for biofuels have important impacts on the environment, such as threat on biodiversity and soil integrity (Schnoor, 2006). Numerous LCAs have been performed on bioplastics as well. A study on bio-based carrier bags in Singapore (Khoo et al., 2010), shows similar observations as those made in our study. The main drawback of PHA-based carrier bags was the production of corn and its transformation into polyhydroxyalkanoate (PHA). Besides, it is interesting to indicate that in these studies, the environmental impacts related to bioplastics were beneficial compared to conventional plastics when the electricity grid mix were switched to renewable electricity sources. Their environmental profile was very dependent on the energy grid mix. However, Piemonte and Gironi (2011) point out that the environmental impacts of bioplastics must take into account the land-use changes linked to cropland to address the issue properly. The same remark can be used for every crop materials. Lastly, LCA on diverse wood coatings have demonstrated the benefits of using 100% solid UV coatings instead of water-based UV coatings or wax-based coatings including from renewable resources (Gustafsson and Börjesson, 2007). Actually, 100% solid UV coatings have the highest wear resistance. Besides, the other coatings show significant environmental impacts due to raw materials production, including crops. Lastly, from all these observations, it can be assumed that the use of natural materials may not be fundamentally a green approach depending on the specific context.

4.2. Hit the road or the railways

As seen in the case study (Cobut et al., in press, corrected proof), transportation is influential on the door life cycle and should not be neglected. Scenarios 5 and 6 tell us that modifying the approach to transport was not as beneficial. In scenario 5, switching from road to railways did not help diminishing significantly the overall environmental impacts. In reality, it may not be as simple to avoid road transportation since railways are hardly able to connect a manufacturer to all clients. Still, efforts could be made to consider rail freight whenever possible because of its low environmental footprint compared to actual road transportation. Aranda Usón et al. (2011) also recommend promoting railway transportation for long distances. However, rail freight promotion should be pondered by the environmental and economical impacts linked to infrastructure development in a geographical context. Scenario 6, which addresses the matter of locally sourced materials, provides interesting results. Even if the overall environmental benefits of this scenario appear low, its impact on transport is yet noticeable and is probably simpler to apply. HDF has a long distance to cover before entering the door manufacturing gates. Even though 98% of this distance is done by railways, dividing the distance by almost an order of magnitude, helps reducing the transport impact by at least a quarter. The covered distance is made by truck instead of train. This means that only by having a local manufacturer and supplier, the difference can be important on environmental impacts, and if it is noticeable for only one of the product component, trying this method for the most part of the product raw materials can greatly help in preventing environmental damages. Looking back in 1997, a study from Jørgensen et al. already highlighted the importance of transports and logistics contribution to a product LCA (Jorgensen et al., 1997). They suggested that transportation was sufficiently relevant as to be more commonly considered when performing an LCA. Eventually, when looking at our results, it can be said that transportation is a non-negligible matter. However, as for many wood products companies, the transport impact is delicate since most of the time the plant is located far away from market centers. Therefore, shipping distances for the product are expected to be significant.

4.3. Developing services for the door industry

Closed-loop recycling scenario 7 exhibits the highest benefits with the lowest efforts. The highest benefits lie in the remanufacturing a door by reusing the core assembly that provides the largest environmental impact reduction compared to every other studied ecodesign scenarios. The least efforts results from the fact that the door manufacturer does not have to find other suppliers, machinery or anything related to the plant; the scenario can be put in place with the actual technology on-site. Doors recovery becomes the main issue in this scenario. After 40 years of door service life, the relation between the client and the manufacturer is most likely not to exist anymore. The idea of door rental might be unsuitable for such long-life products. It might be considered instead, that standard commercial doors supply may come from any site as well as from any manufacturer. Services could be developed to facilitate the link between the building sites, demolition companies and door manufacturers. This kind of service is only possible in the case of standard commercial doors since their manufacture follows the WDMA standards specifications (WDMA, 2006). Despite the major environmental benefits of this scenario, attention should be drawn on used doors supply flow. It may not be possible to rely only on this source of raw materials for door manufacturing and virgin raw materials may yet still be needed. The life-span of a commercial wooden door must also be taken into account when choosing this option. Vijavaraghavan et al. (2013) expose the challenges and opportunities of remanufacturing in closed loop production systems. The main opportunity appears to lie in profitability. Price reductions can be as high as 50% for remanufactured products compared to new products. It can also help companies applying new business strategies, such as a product-service system. Another opportunity cited is the ecological impact of remanufacturing, as can be seen from our results. The main challenges are small lot sizes, unknown conditions of the cores and poor availability. Also technical information and documentation on the products might be difficult to get. This is mainly a problem if the door manufacturer receives products that have not been produced in-house.

4.4. Energy recovery

As seen in scenario 8, fossil fuels substitution for heat production, using chips from the door, has negative environmental impacts for human health and ecosystem quality due to emissions from the burning process. However, as seen in these results as well as in various studies (Jungmeier et al., 2003; Laurent et al., 2011; Sathre and O'Connor, 2010), it has brought a significant score reduction on climate change and resources categories. The use of an approximate unit process from ecoinvent made it impossible to evaluate the impact of burning resins and adhesives contained in the door chips. Actually, the negative impacts of contaminated wood wastes can be controlled through the use of proper high-temperature and high-filtration furnaces, but those processes were not currently available in the chosen database. Jungmeier et al. (2003) are very specific about the fact that using this kind of bioenergy might be CO_2-neutral but not CO_2-free. They stress also the need to compare energy generation to other waste management options to make informed decisions.

4.5. Biogenic carbon

The carbon stored in wood products has not been calculated separately and added in our models. The ecoinvent database has been selected to choose wood products processes from. Nevertheless, the carbon allocation correction, proposed in the database to take into account carbon storage in wood products, is not relayed to LCA results by IMPACT 2002+. Therefore, by accounting for carbon intake from forest and the following storage in wood products, obtained results may be expected to vary from the presented work. In addition, 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; Leturcq, 2014; Sathre and O'Connor, 2010; Skog, 2008). In the present study, the door disposal in a sanitary landfill was not treated as carbon storage. It is fair then to prospect that accounting the stored carbon during landfilling may have changed the environmental impacts contribution of the end-of-life to the total score of the door by lessening it, and maybe balancing waste transportation to landfill impacts. It may also have given supplementary perspectives for the end-of-life alternative scenarios.

5. Conclusions

Eight ecodesign scenarios were stemmed from the LCA results presented in a previous study (Cobut et al., in press, corrected proof). Through assessing the alternative scenarios with the business-as-usual state, using comparative LCA, it has been possible to identify several promising paths.

The least effective alternative was the scenario dealing with wheat straw. That scenario actually worsened the environmental record by 100% or more, largely due to the chemical pre-treatment of wheat-straw particles. Learning from this result, we strongly recommend that an LCA should be performed on bio-based materials in order to be informed of their benefits when compared to conventional petrochemicals alternatives on the basis of a functional unit.

Using pine tannins in the resin formulation of core particleboards helped reducing significantly the environmental profile of the whole door system by at least 20% in all four damage categories. Besides, in a nearly zero-waste forest product industry, one of the only remaining waste is bark (Bowyer, 2012). By promoting the use of tannins from pine bark or by-products in the formulation of bonding resins, bark waste could become a raw material in many

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other product systems. The observed benefits and the validation of this technology through industrial trials in Chile, make this solution interesting and applicable in the short-term.

About the alternative transport scenarios, it was observed that changing transport mode could provide significant environmental impact reductions (around 30% when looking at raw materials transportation impacts specifically). However these reductions were not significant in comparison to the overall life cycle door impacts and considering coefficients of variation of damage scores. Transportation can have noticeable impacts on the LCA results of products and decisions should be made accordingly, whether it is by promoting distribution by rail or by finding manufacturers in a local area whenever possible or applicable.

The remanufacturing option with the core assembly reutilization exhibited the largest benefits in terms of environmental damage reduction over the whole life cycle, even when considering damage scores variation. One reuse of the core assembly permitted to save at least 25% of the original score regardless of the damage category. Remanufacturing could be a short-term option without the need for new technologies nor new suppliers. It does require though the development of retro-logistics systems and services.

The limitations of these results lie in two main aspects. Firstly, this study is based on data that are specific to North America and the province of Quebec, such as electricity grid mix and transportation processes. Secondly, assumptions such as the choice of impact assessment methodology, the functional unit, system boundaries, allocations and the lack of process data bring uncertainty in the results. Certainly, an uncertainty analysis on each alternative scenario damage scores could have shed more light on alternative scenarios beneficial range.

Finally, more research and development should be performed to successfully apply remanufacturing in an industrial environment. The potential of recovery of used doors in buildings should be investigated for sourcing purposes. The mechanical behavior and quality of the reused core component should also be analyzed, especially around hardware fitting areas.

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