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Life cycle assessment and cost analysis of hybrid fiber-reinforced engine beauty cover in comparison with glass fiber-reinforced counterpart

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ABSTRACT

Life cycle assessment is a useful tool that helps to quantify the ecological impact of a product. It also enables us to compare two products. Regardless of its weaknesses, this tool is by far one of the best methods introduced and is one of the most complicated techniques available for environmental assessment. While the benefit of using bio-based materials instead of synthetic materials is well known, to date very few studies are available comparing the two products. The aim of this paper is to compare a currently available car engine beauty cover with a hybrid bio-based cover. This study's results show that the new hybrid materials not only perform better in terms of emissions during car operation (because of the fuel savings resulting from lightweighting), but that their production and end of life is also environmentally benign. A cost analysis of the two types of engine covers shows that the new hybrid materials are a good substitute for current materials because their manufacture costs half that of current materials.

1. Introduction

Lightweighting is an important topic for improving fuel consumption and reducing emissions in the automotive and aviation industries. It is well known that the amount of fuel consumption is proportional to vehicle weight. On average, each reduction in a car's weight of 10% can save up to 8% on fuel consumption. (Stans and Bos, 2007; Van den Brink and Van Wee, 2001). Lightweighting is more valuable in the front of the vehicle, especially the engine area, because of the necessary balanced ratio of front-to-rear weight distribution (Wordley and Saunders, 2006; Woods and Jawad, 2000). Another important concept in lightweighting is secondary weight reduction, also known as “mass decompounding,” (Verbrugge et al., 2009) the principle by which a lighter car can have a smaller engine with no decrease in performance, in comparison with the original car. A very good demonstration of this fact is the MMLV project (Bushi et al., 2015). Most emission reductions are due to the use phase cycle or driving phase of the lighter car; however, using bio-based materials could also be a better choice in the production and disposal phase; it may even cost less than current materials.

A recent study on a grille shutter housing made of three different composites (glass fiber-reinforced composites (30%), cellulose fiber-reinforced composite (30%), and kenaf fiber composite (40%)) showed that using cellulose fiber to reinforce the part is 39.5 MJ less energy-intense than using glass fiber counterparts (Boland et al., 2014).

Some important research on the subject of LCA for lightweight materials took place in the late 1990s. In one of the earliest studies of this kind, researchers compared hemp fiber-reinforced side panels with acrylonitrile-butadiene-styrene (ABS) side panels. These researchers compared the LCA of the two parts and reported that production of the part made of hemp fiber-reinforced composite required 59 MJ, which was more than 55% less energy-intensive than production with ABS thermoplastic materials. The only major drawback was the amount of NOx released: although the release was still less for the hemp fiber parts, the emissions were not as good as expected (Wötzel et al., 1999). Similarly, another study on hemp fiber demonstrated comparable results for bus body components (Schmehl et al., 2008). Das (2011) compared a carbon-fiber floor pan with a steel floor pan and showed that carbon fiber was not better than steel; however, he argued that changing the source of the carbon fiber to lignin would help the fabrication of the carbon fiber to be less energy-intensive. Like the previously mentioned researchers, Das also reported that regardless of the composition and source of the carbon fiber, steel performs better both in terms of NOx emissions and human health (Das, 2011). Existing research also reflects the trend toward replacing conventional materials with their bio-based equivalents: for example, Luz et al. (2010) replaced talc with sugarcane in an interior aesthetic and found a decrease of 4.5% in the energy required for production. The same year, Alves et al. (2010) replaced glass fiber with jute fiber to produce the structural front bonnet for an off-road vehicle; results indicated that although the

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production phase did not favor jute fiber, the use phase compensate for that and the whole life cycle did favor the jute fiber.

In addition to these materials, researchers tried out many different bio-based materials as substitutes for conventional materials. Some of these materials included flax, wood paneling, coconut fiber, cotton fiber, cellulose fiber, foams, kenaf, cork, sawdust, lignin, and agricultural residues (Diener and Siehler, 1999; Çinar, 2005; Finkbeiner and Hoffmann, 2006; Birat et al., 2015; Faruk et al., 2014; Boland et al., 2014; La Rosa et al., 2014; Nourbakhsh and Ashori, 2010; Najafi et al., 2006; Boland et al., 2015).

This study's objective is to perform a life cycle assessment and production cost analysis of an engine beauty cover made of two different composite materials: namely, glass fiber-reinforced polyamide composites and hybrid cellulose-and-carbon fiber-reinforced polypropylene composites which were developed at the Center for Biocomposites and Biomaterials Processing, University of Toronto's Faculty of Forestry (CBBP). The study covers the comparison from cradle to grave, ignoring automobile use phase and its fuel savings.

2. Methodology

2.1. Life cycle assessment

Life cycle assessment (LCA) is a robust process (well-defined by ISO standard family 1404X) to calculate the effects of processes, products, and services on our planet. It is even possible to directly compare products, processes, and services (International Organization for Standardization, 2006a). According to ISO standards, the LCA has four distinct stages: 1) goal and scope definition, including the description of the system boundaries and functional units that determine what the system includes and what is ignored, what processes are backgrounded, and so on; 2) inventory analysis; 3) impact assessment; and 4) interpretation.

The goal of this study is to compare the emissions from the current glass fiber-reinforced engine beauty cover with its hybrid cellulose/carbon fiber-reinforced counterpart during the production phase and up to the end of life, which, in North America, is usually in a landfill.

2.1.1. System boundary

The scope of this research is cradle to grave, starting with the extraction of the necessary materials, such as the growth of the tree used for natural fiber, extraction and refinery of oil for material and energy, extraction and processing of natural gases, extraction of coal, and other energy sources such as renewable and nuclear power. It follows these processes all the way to emission and landfill. Figs. 1 and 2 show the system boundaries and processes in the life cycle of bio-based and conventional engine covers.

2.1.2. Functional unit and scope definition

This study's functional unit is an engine beauty cover that will cover a generic V6 engine of a Ford SUV/pickup truck to provide cosmetic appeal, isolate the heat from the engine, and reduce noises. The cover will be expected to last for 25 years or 290,000 km, whichever comes first. The reference flow for the current research is one fiber-reinforced plastic engine beauty cover that could be either hybrid or glass fiber-based, injection-molded, and estimated to have a life span of over 290,000 km or 25 years. This part will be shredded and sent to a landfill after its life span. The total volume for the part is 957.98 cm^3, with fiber content evaluated based on weight. A unit composed of 30 wt% (glass fiber and mica group minerals mix) is assumed to perform similarly to one of 30 wt% (cellulose fiber and carbon fiber hybrid) (Table 1). Both compounds contain up to 5% proprietary materials (excluded from our calculations), and both compounds meet the manufacturer's minimum standard requirements.

2.1.3. Method, assumption, and impact limitations

This study included only unit processes that contribute more than 1% to system total flows of mass, primary energy, and environmental pollutants. It excluded fuel consumption during the product's use phase, which has been reviewed elsewhere (Akhshik et al., 2017). This LCA study will follow only the landfill scenario for the end of the product's life; this is the most common practice for the plastic composite parts in North America (Stagner et al., 2013; Miller et al., 2014). We assume that the engine beauty covers were sent to the assembly plant with the average mileage of the real distances.

Both engine beauty covers contain up to 5% proprietary additives, which we have excluded from our calculations. Avoided burdens method was used for the calculation of the recycled materials like the one in the polyamide (20%).

For modelling the impacts, we used US EPA TRACI 2.1 for both engine beauty covers. Data categories were both primary and secondary, selected based on impacts as indicated by TRACI (Bare, 2012) and also based on the availability of data in the databases. We collected landfill data from the European generic database and confirmed those using Canadian sources. All other secondary data came from OpenLCA (GreenDelta GmbH, Germany 2014), SimaPro (PRéConsultants, The Netherlands 2015), Gabi (Think step, Germany 2015), GREET (Argonnenational lab, 2015), and NREL (NREL, 2012) databases. For the calculations, wherever no data were available for North America, we used European data.

This study did not consider the environmental impact of cardboard manufacturing, recycling, and packaging because most auto manufacturers and the OEMs recycle their cardboard efficiently. The study also excluded part reuse because it did not fall within the 1% criteria.

The electricity calculated for the energy consumption was based on the average Ontario electricity grid mix during the year 2016. We calculated all prices in the cost analysis in Canadian dollars and converted them to US dollars using a conversion rate of 1.2:1. Manufacturing energy costs, was estimated based on the addition of the prices for each sources of the energy that was used for manufacturing the part. For the purpose of these calculations the available energy prices in KWh were used. Materials cost was calculated for making 1 million parts per year, based on the actual quotes from the material producers. This includes the produced scraps and the material loss due to the manufacturing, shipping and handling. Processing and transportation cost, for both parts, were rounded up to 1 USD for both types of the parts. This includes injection molding machine rate, labor and transportation of parts and materials between the gates.

2.1.4. Transportation and logistics data

We calculated all the transportation and the logistics data based on the actual distances between gates unless mentioned elsewhere; the total transportation data for the main materials follow:

For the current materials, minerals traveling for 1400 km by truck and all other materials (including minerals) will travel for 1260 km to the OEM gate. For each 1 kg of mineral sent to the compounder, 5 kg of composite materials will be sent to the OEM by train. The engine beauty covers are shipped by truck to the assembly plant, which has on average distance of 1134 km.

For the hybrid materials, the carbon fiber is traveling for 1258 km by truck, and the pulp travels for 500 km by ship and truck, as Table 2 shows.

2.1.5. Multi-functionality and allocation

We have encountered only one multifunctionality in the production of the hybrid engine beauty cover. The wood fiber production was either a by-product of the construction wood or pulp and paper. Moreover, for the plastic production, according to the databases, an allocation appears to exist for the portion of the flow of the mass. We use the avoided burden approach to avoid recalculations for polyamide recycling.

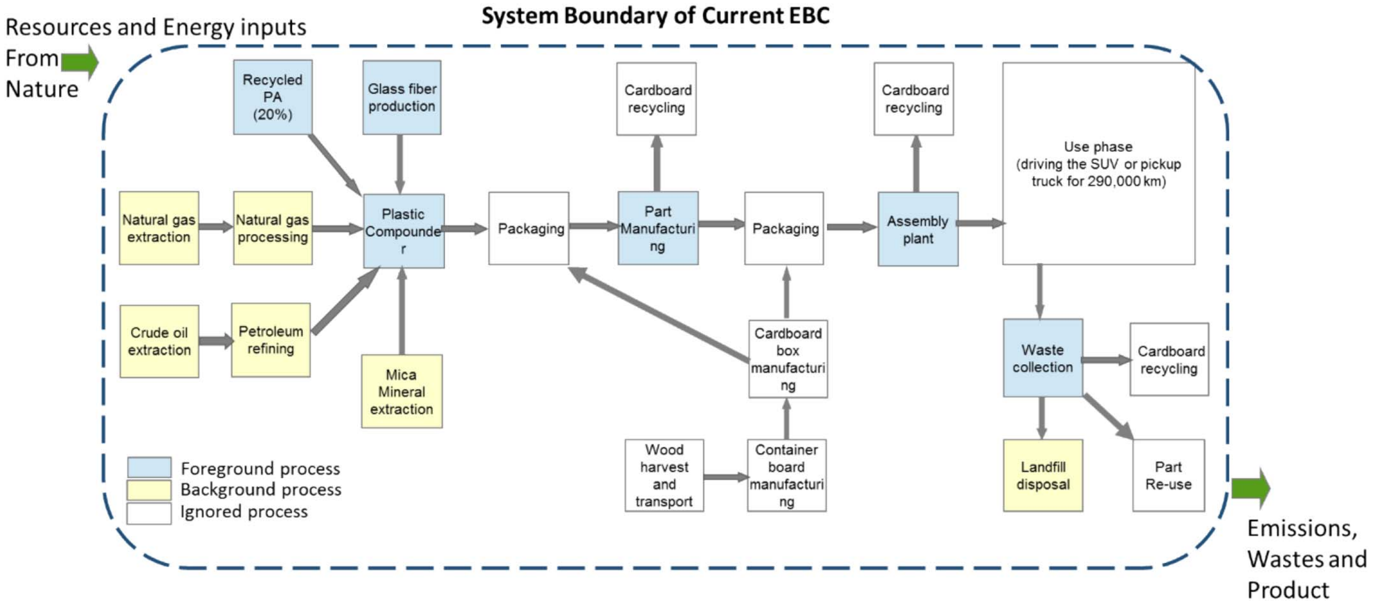

Fig. 1. System boundary and processes in life cycle of a conventional engine beauty cover.

2.1.6. Data quality requirements

This study's geographical coverage is the country of Canada and/or the continent of North America. All the gathered data for this study are less than 10 years old; most of the data are less than 4 years old. The average technology assumed for purposes of this study is based on an average Canadian/North American technology mix. We have collected all primary life cycle inventory data through collaboration with mining industries, parts manufacturers, material suppliers, landfills, and researchers.

2.1.7. Inventory

Table 3 contains the inventory of the conventional and hybrid materials needed to meet the required reference flow and used for calculations.

Table 1
Material composition for two engine beauty covers used in this study.

Materials	Weight	Fibers	Matrix
Current engine beauty cover	1.322 kg	0.132 kg glass fiber 0.264 kg mica minerals	0.185 kg recycled polyamide 0.740 kg virgin polyamide
Hybrid engine beauty cover	0.992 kg	0.198 kg cellulose fiber 0.099 kg carbon fiber	0.665 kg virgin polypropylene

2.2. Description of the system and the life cycle

2.2.1. Production phase

We calculated the data for the production phase from both primary and secondary sources, adding together each portion of the hybrid and

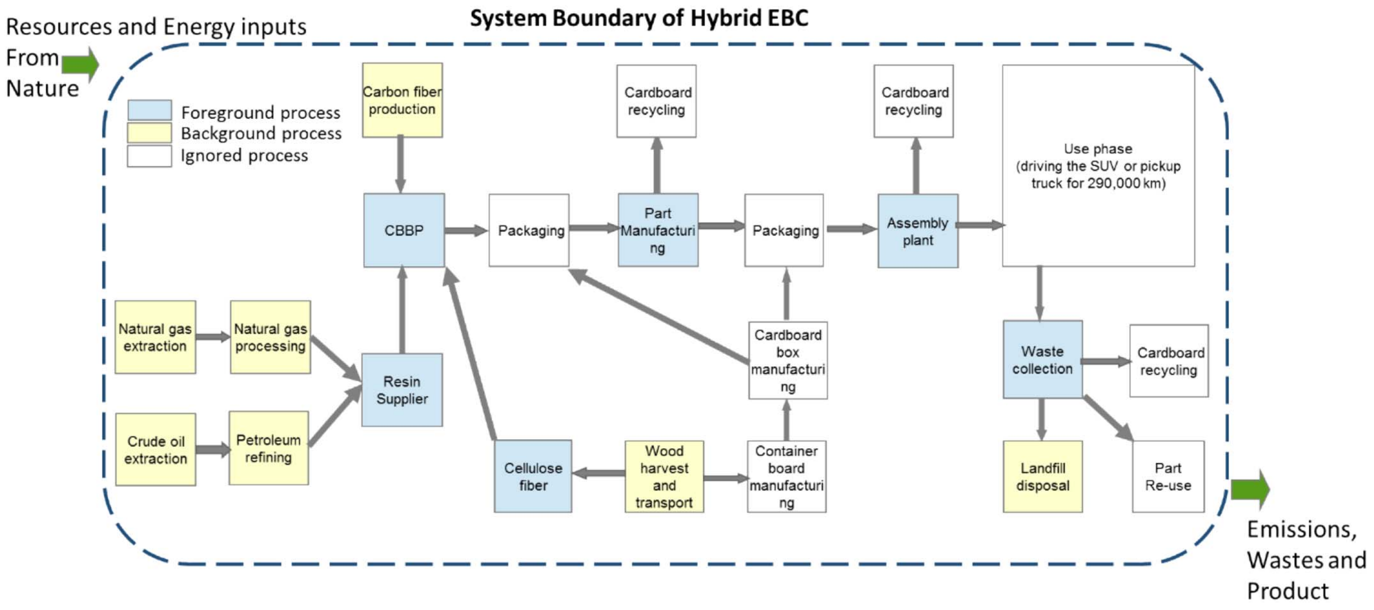

Fig. 2. System boundary and processes in the life cycle of a hybrid engine beauty cover.

Table 2
The logistic data for both engine beauty covers. These are the mileage that materials are traveling for making one engine beauty cover, based on the common transportation practices from the freight companies.

Materials	Distance	Method
Carbon fiber	1258 km	Truck
Pulp	500 km	Truck/Ship
Minerals & GF	1400 km	Truck
Resin (PP)	283 km	Truck
Resin (PA)	530 km	Truck
Compound (Hybrid)	368 km	Train
Compound (Current)	1260 km	Train
Part (both)	1134 km	Truck

Table 3
Inventory of materials needed for making one engine beauty covers, including the waste.

Current materials	1.381 kg
Glass fiber	0.138 kg
Mica	0.276 kg
Virgin polyamide	0.773 kg
Recycled polyamide	0.193 kg
Hybrid materials	1.037 kg
Cellulose fiber	0.207 kg
Carbon fiber	0.103 kg
Polypropylene	0.695 kg

the current composite material to find the total emissions, which includes materials extraction and processing, transportation, compounding, and part manufacturing. For calculation of 20% recycled content, we used the following numbers: based on different reports and also communications; we calculated recycled PA energy demands for production as between 0% and 35% less energy intensive than that of virgin PA. Therefore, we assumed the average case scenario and considered that using 1 kg of recycled plastic consumes 14% less energy and resources than using virgin plastic, confirming this number by converting greenhouse gas emissions (Cause Canada, 2015) to total energy demands. We used 14% as the basis for calculating recycled content, reduced from the total consumption of the energy and materials for the total polyamide (virgin and recycled). In the injection molding process, we calculated an average of 0.045 kg of rigid plastic part scrap per kilogram of injection-molded plastic, as mentioned in the NREL databases (NREL, 2012); we confirmed this figure with the part manufacturers.

2.2.2. *Use phase*

The use phase has been discussed elsewhere; this study therefore ignores it. For more information, please refer to the reference (Akhshik et al., 2017).

2.2.3. *End of life*

Even considering all recycling technology improvements, we find that recycling of the used part is still not cost-effective, especially for the fiber-reinforced composites. Therefore the low-cost option, landfill, is favored in North America. (Stagner et al., 2013). Aside from cost-effectiveness, there are numerous reasons for not recycling these materials, such as complexity of recycling, lack of established methods for incinerating fiber-reinforced composites, and dismantling difficulty (Winslow et al., 1998; Stagner et al., 2013; Toth et al., 2014; Stagner et al., 2012). Based on confirmation from landfills in Canada and the US, as of today we may safely assume that plastic parts mostly are not recycled at the end of a vehicle's service life and become automotive shredder residue (ASR) before reaching the landfill. Aside from the known landfill operations emissions (such as machine and vehicle fuel consumption), after about 10 years in the landfill ASR produces emissions of methane (Bogner et al., 1995; Czepiel et al., 2003; Al-Salem et al., 2014), which, as one of the greenhouse gases, is therefore calculated as part of GHG emissions.

2.3. *Sensitivity analysis*

Both the International Organization for Standardization (ISO) and the Canadian Standard Association (CSA) require sensitivity analysis to be performed for all LCA that contains assumptions (ISO 14044:2006; CSA SPE-14040-14). Therefore, for all our study's assumptions we used the original calculation as the reference, considered the variation in our scenario, and compared the two results. The sensitivity analysis—usually reported as the difference between the original calculation and the other scenario—is either greater than or less than 10% (CSA group, 2014). One assumption this study considered was using the extrema available data from around the world as an approximation of the process and flow data that were not available for our geographic regions. Another consideration could be a change in the materials, designs, and manufacturing processes. We have also performed the test for several available electric power grid mixes and fuel sources (International Organization for Standardization, 2006b).

2.4. *Cost analysis*

As the ultimate goal of corporations such as OEM and auto manufacturers is maximize profits, providing a price comparison for new material is important. Replacing a material with an expensive alternative is not really practical (unless there is a matter, such as a safety concern, that overrides the cost consideration), even if the alternative is environmentally advantageous. Therefore, here we used all the energy requirements to make and dispose the engine beauty covers and required materials to estimate the cost of the parts. We then used the estimated cost to compare the two parts in terms of price. As both the materials and the energy required for manufacture were priced in Canada, we calculated all costs in Canadian dollars and then converted them to US dollars using a conversion rate of 1.2:1. We based the cost analysis of the parts on the bulk price for making 1,000,000 parts per year and assuming the current market price of the materials remains constant.

3. Results and discussion

3.1. *Data quality assessment*

We based the data quality evaluation on Weidema and Wesnaes's (1996) method. Although there are more advanced and accurate methods are available, this method is one of the simplest available methods for the data quality assessment. In Weidema and Wesnaes method, we simply draw a table of data quality indicators and we assign the best data a ranking of 1 and the worst data a ranking of 5. Table 4 shows the quality of the data assessed in this study; the data quality indicator scores show that the data considered were of good quality.

Table 4
The data quality check was done based on the method of Weidema and Wesnaes (1996).

Data quality indicator	Score	Explanation
Reliability	2	Some of the data was based on assumptions
Completeness	1	Complete
Temporal correlation	3	The data are less than 10 years old
Geographical correlation	3	All data are from North America, except for landfill data which was from Europe, but it was verified by Canadian practices
Technological correlation	2	Data are average recent North American technology mix

Table 5
Total energy consumption and the energy sources, water, wood, and waste comparison for both the hybrid and current engine beauty cover. The table also contains the result of TRACI2.1.

	Current	Hybrid		Current	Hybrid
Coal (MJ/part)	4.65E + 01	2.39E + 01	Global warming air (kg CO2 eq)	2.03E + 01	8.76E + 00
Oil (MJ/part)	8.66E + 02	3.28E + 02	Acidification air (kg H + moles eq)	3.53E + 00	2.39E + 00
Hydropower (MJ/part)	2.32E + 00	1.23E + 00	HH criteria air (kg PM10 eq)	9.45E-03	4.96E-03
Natural gas (MJ/part)	4.58E + 02	3.96E + 02	Eutrophication air (kg N eq)	1.46E-03	5.25E-04
Solar (MJ/part)	1.51E-01	8.30E-02	Eutrophication water (kg N eq)	1.09E-03	2.16E-04
Uranium oxide (MJ/part)	1.20E + 01	5.83E + 00	Ozone depletion (kg CFC-11 eq)	3.72E-07	1.41E-07
Water (m^3)	3.06E-02	6.67E-02	Smog air (kg O3 eq)	8.96E-01	3.39E-01
Wind (MJ/part)	1.47E + 00	8.25E-01	Smog air (kg O3 eq)	1.24E + 01	6.83E + 00
Wood (MJ/part)	7.30E + 00	8.01E + 00	Human health – Cancer(Cases)	1.02E-09	8.03E-10
waste (kg/part)	2.12E + 00	1.37E + 00	Human health – non-cancer(Cases)	6.89E-07	3.99E-07
Total energy consumption (MJ/part)	1.39E + 03	7.64E + 02			

Table 6
The estimated cost of producing a single engine beauty cover from natural or glass fiber-reinforced composites.

	Current part	Hybrid part
Total cost (USD)[a]	$31.39	$18.27
Total material cost (USD)	$2.94	$2.90
Total energy cost (USD)	$27.45	$14.37
Fossil fuel %	97.87%	98.14%
Renewable energy %	1.70%	1.35%
Processing cost (USD)	$1.00	$1.00

[a] The price calculation is based on the assumptions of all the materials and energy price remain the same for a year. All the prices converted to US Dollars from Canadian Dollars by a conversion rate of 1.2:1.

3.2. Results of LCA

We completed the LCA based on the collected data, and the calculations, in order to have a better knowledge of the data a sensitivity analysis was performed which will be discussed further. Assessing the environmental impacts was performed using the US EPA TRACI2.1 analysis as previously described. Table 5 shows the results of the TRACI; for a better view, both results are shown on a percentage scale to facilitate comparison.

As Table 5 shows, all TRACI indicators are better for the hybrid materials than for the current materials. Among the indicators, ironically water eutrophication was the highest, over 5 fold more than the hybrid materials, and human cancer was the closest, with over 1.27 times difference.

Total Energy consumption for the lifecycle of the engine beauty cover was calculated based of the method described before and as it was expected hybrid materials outperformed the current materials. As indicated in Table 5, The required energy for making the part with hybrid materials (cumulative energy demands), including the biogenic carbon and all the energy sources (renewable and non-renewable), is around 45% lower than making the part from current materials. These calculations are based on the fact that lightweighting will save money on materials, including extraction, transportation, and waste collection.

Table 5 also shows a general comparison overview of the current and hybrid materials. As you can see, the details of the energy consumed by the source of energy are different for each part. The oil consumption for current materials is over 2.6 times that of the hybrid biomaterials, and natural gas consumption is over 1.1 times higher. For hybrid materials, the consumption of water is over 2 times that of the current materials, which is an important consideration for areas with water scarcity or pollution problems; and obviously wood and carbon fiber increase the necessary amount of wood by almost 9% for our hybrid biomaterial-based engine beauty cover. In terms of waste produced, the hybrid material was better, as anticipated.

3.3. Sensitivity analysis

We performed all sensitivity analysis for this study on the emissions using Crystal Ball v11.1.2.4 (Oracle, USA); results demonstrated that with all the possible changes in our data the emissions and energy calculations were still well under 10%.

3.4. Cost analysis

This study also examined the respective costs of producing 1,000,000 units from both materials. If we only consider the cost of materials, the hybrid materials are cost-competitive with the current materials. Moreover, in terms of the cumulative energy required for the entire production phase, the hybrid materials outperformed the current materials (by about 46% of the manufacturing energy cost). Despite containing expensive components such as virgin carbon fibers, the hybrid materials are tend to be price competitive with current materials and if we consider the reducing price trend for carbon fiber, these kind of hybrid materials are indeed promising. Table 6 shows the cost analysis result.

3.5. Discussion

This study compared the environmental impacts and the costs to manufacture an under-the-hood part (engine beauty cover) using two different materials: glass fiber reinforced polyamide, which is currently used, and a natural fiber/carbon-fiber hybrid reinforced polypropylene. Considering all the uncertainties, manufacturing the engine beauty cover with the hybrid composites is a cleaner process in terms of environmental emissions and energy demand. Other studies confirm these results (Luz et al., 2010; Joshi et al., 2004; Boland et al., 2014; Batouli et al., 2014a; Xu et al., 2008). Although production of carbon fiber is very energy-intensive (1800–2000 °C) and expensive, the cost of hybrid composite materials is slightly less than that of the current glass fiber based part. The actual cost saving occurs during manufacture and transportation, expenses which increased for current materials by about 46%. Other advantages of using the hybrid composites for the OEM is that these materials are very similar in terms of processing and handling: for example, the injection molding process does not require additional training or consideration. These materials usually require a lower injection temperature and a higher holding pressure than do the current materials.

Substitution of the hybrid bio-based materials for the current materials demonstrated a reduction in energy demand (over 1.6 fold) and waste disposal cost (by over 1.5 fold); however, hybrid bio-based materials are not as good as current materials in terms of water (over 2 times worse) and wood consumption (almost 1.1 times worse), as Table 5 shows. In terms of wood consumption the difference is negligible because the hybrid material is actually contains wood fibers. In terms of water consumption, especially if the strategic guidelines for the country indicates to adopt the methods and materials that preserve water, extra caution should be taken and these materials may not be the best solution. However considering the country of production (Canada) and also the urgency of the need for reduction in greenhouse gas emissions and also energy demands, these materials should be considered seriously as a replacement for our current glass fiber materials.

The TRACI results demonstrated that none of the indicators for the current materials are as good as those for the hybrid bio-based materials. While some researchers have reported that biomaterials are not very good in terms of eutrophication (Wötzel et al., 1999), the materials in this study are not an agricultural-based product; no fertilizer is used in their production phase, and hence the eutrophication (combined air and water emissions) for the hybrid bio-based materials is 3.43 times less than that for the current materials.

In terms of human health – cancer which is the number of the cases reported on the cancer causing by our materials and methods, it seems that our materials is not as good as other TRACI indicators, and the difference is only 27%. This could be an indication of the fact that most of the cancers are caused by the matrix and the energy consumed, however, as shown, replacing the glass fiber with hybrid natural/carbon fiber may decrease the chances of cancer.

4. Conclusions

This study performed a life cycle assessment comparison for manufacturing and disposal of the engine beauty cover made of two different composites, namely, glass fiber-reinforced polyamide and cellulose/carbon fiber-reinforced polypropylene. Both materials met manufacturer material specification standards and could therefore be treated as equivalent. In this study, we showed that hybrid cellulose/carbon fiber composite performs better in terms of all environmental impact categories. However the hybrid materials performed worse than the current materials in terms of both water and wood consumption. Although these materials have a reputation for high impact in terms of eutrophication, this is not the case in this scenario, as not using fertilizer in the silviculture process, mitigates the impact of eutrophication. Lightweighting has been studied for decades, and most reports indicate that the benefits of bio-based materials will come from the fuel savings related to lightweighting during the use phase. However, we show here that lightweighting can also be beneficial during the production and end of life phases. Moreover, in terms of cost, making the part with the hybrid biomaterials is less expensive, especially with regard to manufacturing and transportation energy demand, even though it contains costly virgin carbon fiber.

With all these benefits, switching to biomaterials seems to be the natural next step in auto manufacturing. However, further studies on these kind of materials are necessary, especially as many factories are currently moving toward becoming self-sufficient in terms of energy, and some will have a plan to use 100% renewable energy.

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