Journal of
composites science

MDPI

Article

Green Composites Reinforced with Plant-Based Fabrics: Cost and Eco-Impact Assessment

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Received: 18 December 2017; Accepted: 6 February 2018; Published: 11 February 2018

Abstract: This study considers a green composite under a twofold assessment; evaluating its process-based cost and environmental footprint profile. The initial objective was to project the manufacturing cost and allow for an additional material comparison of alternative scenarios in the resin transfer molding processes. The additional aim is to have an intermediate environmental assessment to assist in selecting materials and adjust manufacturing parameters which would minimize the energy spent and the CO_2 emissions. As it has been noted in numerous applications, the incorporation of natural fiber fabrics, as opposed to glass fabrics, bring together weight savings and consequently cost savings. However, the economic analysis suggests that a glass reinforced composite is marginally cheaper at the production volume of 300 parts (1.9% lower cost) in contrast to a possible green solution (ramie). Considering jute instead of ramie as a reinforcement, the cost gets immediately lower, and further decreases with proposed improvements to the manufacturing process. Additional reduction of up to 10% in the production cost can be achieved by process upgrade. As indicated by the Eco-Audit analysis, 36% less energy and 44% CO_2 per kilo will be generated, respectively when swapping from glass to ramie fabrics in the production of the automotive hood.

Keywords: polymers; process-based cost modeling; eco-audit

1. Introduction

There is growing support in the technical and scientific literature that green composites can provide mechanical properties analogous to synthetic composites and, therefore, will replace their traditional counterparts in future automotive applications [1–4]. Substituting petroleum-resourced automotive compounds typically of reinforced with glass-fiber polymers (GFRP) by composites of renewable substances is becoming increasingly imperative, not only as a modern trend but as a necessity towards a more sustainable society in terms of materials use [5,6]. Consequently, it is anticipated by both industrial practice and academia that producers, end-users and the environment may benefit equally from that shift [7,8]. Broadly speaking, the term "sustainable" is used to describe composites which are made entirely from annually renewable materials or a mix of synthetics and natural products at a discretionary percentage. In that sense, the former is considered more environmentally friendly when compared to composites made of petroleum resourced constituents like GFRPs.

One way to balance sustainable materials use and manufacturing cost in automotive panels is by the use of composites containing renewable materials. A number of automakers and academic studies have explored and presented practical examples of plant-based solutions for automotive parts including trim parts in dashboards, door panels, parcel shelves, seat cushions, backrests, cabin linings and so on [5,9–15]. One can see an increasing interest in replacing fiberglass by introducing natural plant fibers such as jute, flax, hemp, sisal and ramie because of the environmental benefits achieved due to the density of natural fibers comparing to glass fibers [6,12,16–18]. Subsequently, green composites have the potential of multiple gains in terms of economic/mechanical performance, environmental impact and public acceptance when compared with fossil-derived plastics, metals and traditional synthetic resourced composites.

Some researchers have combined technical cost modeling along with life cycle assessment (LCA) to complement an analysis of composite aircraft components [19] or Life Cycle Cost (LCC) coupled with LCA [20,21] to analyze the economic and environmental impact associated with a product. However, for the present study, considering cost implications of logistics and manufacturing processes in different design alternatives is more important, and these are not well estimated by traditional cost models, i.e., technical cost models or LCC. These make use of deterministic historical cost databases and elemental quantities from product design to estimate cost which may lead to inaccurate calculations. For instance, when substituting materials on an existing process, we must also take into account characteristics of the process employed (distinct yields, operating rates, tooling life, etc.), which also need to change accordingly with the material price [22]. The LCC explicitly does not take into account the decision makers' limited ability to make rational decisions under uncertainty [23]. Especially in the early stages of development, as described by Kirchain and Field [22], cost descriptions by accounting systems cannot be used alone to understand how it will vary in response to changes in part design, material, or operating conditions, not to mention wholesale process technology change.

The LCC analysis is a resource and data-intensive process [23,24], making it difficult, if not impossible, to model future costs and various components of cost in disaggregate level. A rigorous approach to such a quantitative assessment requires unreasonable time and effort that risks bringing the discussion to a more qualitative level, or, even worse, abandoning this approach [25]. It incorporates diverse factors in a practical manner with a judicious mix of quantitative and qualitative aspects [24]. In fact, in the literature, there is no formal guideline and reliable past data to perform an LCC analysis [24,26], which appear the main reasons for the tardy adoption of LCC [24]. Additionally, traditional cost models rely wholly on historical data quantities from product design, which may not exist for novel technologies [27]. These cost assessment tools are retrospective, directed toward the performance of existing plants and products and tasked with informing the decisions of plant management rather than the decisions of those in design and R&D offices [22,28]. A possible approach to tackle the above problems is to use a PBCM, which regards cost as a function of technical factors, such as cycle time, downtime, reject rate, consumed materials, equipment and tooling requirements.

The Process-Based Cost Modeling (PBCM) analyses between alternatives of product and process designs to tie manufacturing cost to the technical and design parameters. These models allow the decision maker to make choices early in the design process, avoiding costly strategic errors in product development and deployment [22]. Understanding the effect of technical cost drivers provide insight for managers and engineers on which process improvements are most critical to lower production costs [29]. In general, they all allow for fine tuning of parameters for analytical methods rather than time-consuming experimentation [22]. A categorization of product present cost estimation models including qualitative (intuitive and analogical) and quantitative (parametric and analytical) methods have been extensively reported by Niazi, Dai, Balabani and Seneviratne [30]. The PBCM as introduced by Kirchain and Field and further updated and analyzed by Field et al., integrates operational requirements with physical relationships to evaluate the financial impacts on a manufacturing process [22,31].

In the research field of environmental analysis, a number of studies have assessed the environmental impact of automotive parts made of green composites [12,32,33]. However, they did not incorporate economic metrics in their analysis to further support their sets of choices. Additionally, the LCA technique is extremely data intensive and thus the lack of data can restrict the conclusions that can be drawn from a particular study [34]. For instance, LCA is primarily focused on detailed environmental reports for finished products [35] and requires information that is mostly unavailable in early stages of concept development [35–37]. Furthermore, 80% of the environmental burden of a product is determined in the early stages of design when many decisions are still fluid [35]. Despite

LCA's more accurate assessment of environmental impact and the fact that it has a broader list of environmental indicators, it is time-consuming with respect to the complexity of each process step [38], i.e., setting up inventory data can be one of the most labor and time-intensive stages of an LCA [34].

The Eco-Audit tool has been employed by a number of studies to evaluate sensible heat storage materials [39,40], wall hung boilers [25] and wind turbines [41] for their environmental performance. The tool can be used as an integrated approach to assist in design decisions that are followed by further cost analysis and LCA [37]. An LCA is highly desirable and can provide valuable information about the total environmental performance in a way that the Eco-Audit tool cannot. As such, the Eco-Audit points to the aspects of design that a fuller LCA should examine as a product assessment tool. A rational explanation of the Eco-Audit tool approach is found in the CES EduPack Eco-Audit tool white paper [35]. Few reliable indicators are accounted for when ranking materials and processes within the assessment. These indicators include energy consumption, the global warming potential, and the end of life possibilities (regarding useful, practical scenarios, e.g., of downcycling). This leads to a more "streamlined" method which condenses eco-information of material production into a single indicator, e.g., CO_2 produced per unit weight of material manufactured. Hence, not all parameters provided by a full LCA study are explored. The Eco-Audit foregoes the use inventory data from international databases unlike the primary ones needed in LCA [25], and that is one of the reasons why LCA is more accurate for a more in-depth level of environmental analysis of the system under study. The Eco-Audit tool, although not as thorough as other more advanced tools for LCA, still enables a meaningful comparison of alternatives at a fraction of the effort of building the analysis in terms of energy consumption and carbon footprint. In contrast, more advanced tools for LCA like SimaPro may be more accurate in assessing environmental impact in more depth, they are also in general extremely time-consuming to set up. There is, therefore, a trade-off between time to setup and accuracy of the results, which is in fact mitigated by the uncertainty regarding a number of parameters that need to be in place to use a full LCA which renders its use extremely difficult.

We suggest that under this method, PBCM and Eco-Audit, one can first translate the complex and interrelated consequences of design and process technology changes into a cost metric, followed by an initial idea of the environmental impact in the very early stage of product design. Unlike the researchers Witik et al., 2012 and Yang et al., 2017, we intend to bridge the gap of cost estimation and environmental impact in concept design phase by the combination of the PBCM and eco-impact assessment. These well-established methods are employed as a practical way to assess financial cost and environmental impact for the case of a buggy hood part at the conceptual phase of the product. We utilize this model to guide design decisions when materials and processes are not yet established, but a rough estimation of cost and energy of the design is needed.

2. Materials and Methods

We developed a green composite using a polymer (aliphatic polyester with recycled vegetable oils) and plant-based fabrics in the automotive hood (hinged engine cover) of a buggy vehicle. Our aim is to identify and compare the larger contributors to the environmental burden caused in different phases in the manufacturing of the component. We especially expect to reduce the part's weight and develop a composite that will best balance environmental performance and affordable production cost compared to its conventional counterparts. Ancel Ltda—Rio Claro, Brazil (a composite manufacturer) has been employing an eco-design strategy by exploring plant-based fabrics as promising reinforcements while minimizing manufacturing cost and leading to environmental improvements. This approach contributes to noticeable weight savings (18–27%) which in turn can contribute to a higher maximum range concerning fuel economy while also reducing the atmospheric CO_2 emissions in the long run [12,42,43]. Similar environmental performance findings have been issued by Mitsubishi [15] and Toyota [44] when incorporating natural fiber reinforcements in their car's components. In another example, a 60% reduction in manufacturing energy expenditure can be realized by integrating natural fibers (abaca) on composites panels reported for the Mercedes-Benz A-Class model [45].

Ancel has been working towards the development of a green composite reinforced with natural fiber fabrics in the hood of a buggy vehicle. The latter will comprise a means of transportation intended for urban use, typically along coastal areas. This type of vehicle is designed for a very narrow niche market and therefore the batch size for this target group is limited. The conditions at Ancel's production line are used to describe the operational baseline scenario. Next, we generated a common framework that generalizes operational and financial conditions for each alternative solution, thereby highlighting the technical factors that influence manufacturing cost and plant's characteristics. By definition, the PBCM involves three interrelated and interdependent models: a technical process model, a production operations model, and a financial accounting model which all map in detail the product's and process' characteristics.

The very same baseline scenario regarding its environmental footprint is evaluated via the Eco-Audit, a plug-in tool of CES Selector© (Granta Design, Cambridge, UK) [46]. Eco-Audit incorporates an extensive materials' database where materials records are listed along with their mechanical/environmental performance and production characteristics. From a designer's point of view, the development of more environmentally-friendly products enforces the consideration of environmental aspects in concurrence with traditional technical and economic aspects from the onset of design activities [47]. On a second level, it assists in making materials and process choices that would minimize the energy spent to sequester the CO_2 as much as possible.

3. Analysis and Results

This section covers the results regarding the twofold analysis of the economic and environmental performance of the baseline scenario as compared to the ones made of sustainable materials.

3.1. Process-Based Cost Model in General

This economic analysis examines how the choice of materials and processing technology affects production costs and can be used by the decision makers to make better choices when aligning their companies to the future challenges of technology. The first step in the model utilizes a process model that incorporates engineering relationships between the part description and the materials processing technology to determine the necessary processing requirements (e.g., for an injection molding process, these could be injection flow pressure, mold force, etc.). Next, an operations model combines the processing conditions with the desired production scale to determine plant resource requirements (e.g., operating days per year, downtime, etc.). Finally, a financial model applies factor prices and accounting principles (e.g., labor cost, overhead rates, etc.) to the set of resource requirements coming from the operations model in order to determine the production cost. Figure 1 shows a schematic diagram of this model.

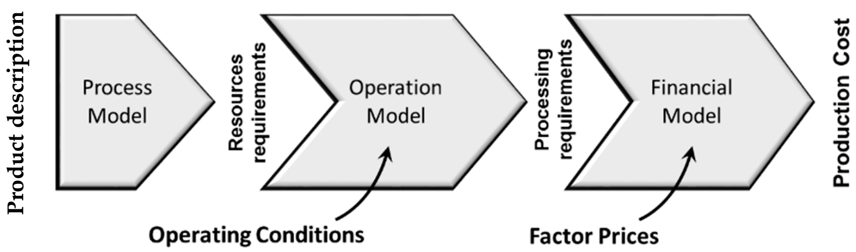


Figure 1. The Process-Based Cost Modeling (PBCM) elements' decomposition.

The process model is parametrically linked to the product description, so all processing requirements are automatically updated when the product description changes. These processing requirements are combined with a production scale (parts per year) in the operations model to determine resource requirements like annual material usage, machine utilization, labor, energy, and building space needs. If the process has multiple steps, the operations model calculates the effective production volume at each process step based on aggregate reject rates. The process is modeled as a single step process for the sake of simplicity. Therefore, it is possible to derive the gross number of parts produced (Production Volume) from the overall target net volume, and the reject rate for the process. The reject rate describes the percentage of manufactured parts, which are expected not to pass the quality specification and need to be scrapped. A total of 3% of rejects is generated for the RTM automotive hoods. Specifically, the effective production volume produced is described by the Equation (1).

$$Effective\ Production\ Volume = \frac{Overall\ Net\ Volume}{(1 - Reject\ Rate)} \tag{1}$$

The financial model applies raw material price, labor wage, building cost, machine costs, and tool costs to the respective resources at the scale projected by the operations model. Machine costs are calculated by multiplying the machine utilization rate with the amortized annual machine investment, using the machine life as the amortization period. Table 1 summarizes the manufacturing-specific issues of the PBCM for the manufacturing scenario. Capital refers to the machines to be used to produce the parts and their support equipment. Labor translates to factory's laborers who operate the machines. Tooling stands for the tools to be used to provide shape to the material and Energy is the amount of required energy for the all the processes deployed. In order to incorporate these investments into a unit cost, the financial model distributes them across time by determining a series of annual payments that are financially equivalent to the initial investment. More details about the calculation of discount rates and building costs can be found in the work of Nadeau, Kar, Roth and Kirchain [27].

Table 1. Main PBCM elements considered for manufacturing.

• Consumables ○ **Raw materials** ○ **Process materials** ○ **Recycling** • Equipment utilization ○ **% of the line required** • Building space • Energy	• Effective production volume (**Rejects are considered**) ○ **Labor** ○ **Indirect** ○ **Direct** • Equipment requirements ○ **Press, tooling** • Capital

3.1.1. Resin Transfer Molding Process Cost Model

The hood part will be manufactured by the Resin Transfer Molding (RTM) process given that Ancel Ltda already owns the necessary tooling and manufacturing know-how for analogous projects. Therefore, its workforce is already familiarized with all equipment and procedural steps as regards the manufacturing steps. The RTM cost model used for this study was previously developed by Materials Systems Laboratory (MSL) at Massachusetts Institute of Technology and adjusted accordingly by the authors to Ancels' workshop conditions. These costs models use a technique developed by Busch and Field and Clark et al., consisting of a spreadsheet-based analytical tool that breaks up the costs of a manufacturing process into elemental process steps [48,49]. This tool entails the outline of the manufacturing process flow, the estimation of the cost of materials, consumables, tools and the estimation of mean cycle times and labor and machines involved. The reference baseline hood part is produced with glass fiber mat reinforcements and thermosetting polyester. The final part weights 2.44 kg, out of which 1.51 kg is the resin and 0.8 kg is the reinforcement (untreated glass mats), the rest of the matrix's materials include curing solutions as additives, promoter, and catalyst.

Bearing in mind Ancel's past projects for similar products, the prospective manufacturing process (baseline scenario) of the hood is expected to be a six-step sequence which includes: resin preparation, fabric cutting, mold preparation, injection, extraction, and inspection. This manufacturing process, with all requirements per step, is depicted in Figure 2.

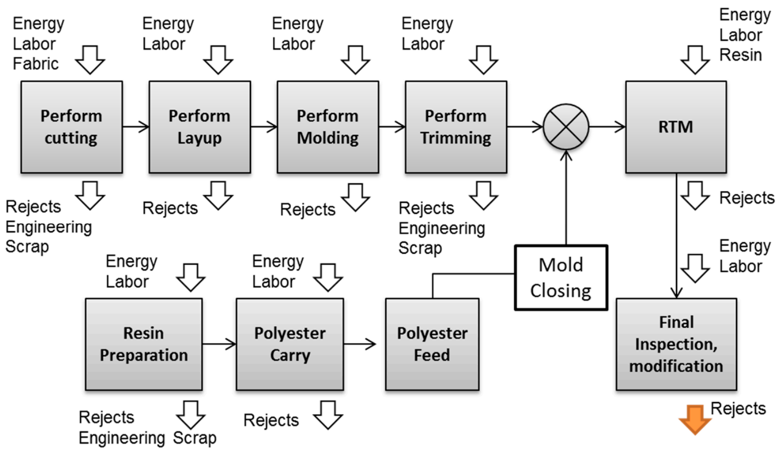


Figure 2. Resin Transfer Molding (RTM) process cost model step sequence in Ancel's workshop.

The process model considers two parallel paths: fiber fabric preparation and resin preparation. Fiber fabric preparation consists of cutting the fiber layers and placing them in the correct layup orientation, placing the layers together, and then trimming them if needed. Resin preparation consists of preparing the resin by mixing it with additives in a resin agitator. Afterward, the resin and catalyst are transferred at the RTM step (see Figure 2) where the mix is injected into the mold and left to be cured. Promoters/accelerators used to speed up and enhance the composite curing in closable molds with no temperature adjustment or pressure. The last step of the process is the inspection where the part is checked for its surface finish.

The annual production volume (APV) of the hood is set to 300 hood parts per year and the plant operates for 302 days per year. It is worth noting that in Ancel, as it generally happens in most Brazilian companies, operates for 8 hours on one shift during weekdays and 4 h on Saturdays. Table 2 lists all the general cost model assumptions used in all economic analyses. Where possible, input values were placed as observed at Ancel's production facility or reported by the producer. For confidential reasons, all currency values have been transformed to an adimensional monetary unit value MU, and were thus subjected to normalization.

Table 2. Assumed plant conditions for the hood production.

APV	300	Parts	**Idle Space**	50	%
Days per Year	302		**Capacity Utilization**	25	%
Wage	4.15	MU/hour	**Auxiliary Equipment**	Included in machine cost	
Unit Energy Cost	0.38	MU/kWhr	**Installation Cost**	20	% of capital cost
Interest	15	%	**Maintenance Cost**	10	% of capital cost
Equipment Life	10	years	**Production Lots Size**	20	parts
Production Life	5	years	**Building Unit Cost**	3370	MU per m^2
			Building Life	40	years
Downtime					
No Shifts	16	hours			
Unpaid Breaks	0.5	hours			
Paid Breaks	0.3	hours			
On Shift Maintenance	1	hours			
Idle	1.3	hours			
Unplanned Downtime	0.8	hours			

Some parameters in Table 2 require some explanation. Idle space is the area surrounding machines that must be kept free in order to allow access around the equipment. The 50% idle space implies that an RTM machine with a 10 m^2 footprint requires 5 m^2 idle space around it. The RTM machine is assumed to have a use life of 10 years. Building space costs MU 3370/m^2 and is amortized over

40 years. Maintenance costs for all equipment are 10% of capital costs. The plant is assumed to be 5% utilized as other processes are taking place in the workshop like hand layup, and spray lay-up for other production parts which require much more space than the RTM. Downtime, comprising all the time when equipment is not productive, totals 19.9 h per day. This includes 16 h when there are no shifts, 0.5 h for unpaid breaks, 0.3 h for paid breaks, 1 h for on shift maintenance, 1.3 h of idle time, and 0.8 h of unplanned downtime.

3.1.2. Technical and Economic Related Parameters

Labor

The labor content that was documented at Ancel is the following. Two direct workers on the RTM line responsible also for the fabric cutting, mold preparation injection and demolding. In addition, one direct worker is on the rework line and one indirect worker supervising the entire production workshop.

Tooling

A versatile RTM injector DTF-500 machine (Fibermaq Equipamentos Ltda, Sao Paulo, Brazil) used for injecting resin and catalyst simultaneously at a constant pressure based on a piston type apparatus driven by compressed air. This is a semi-automated injector machine with a hand pistol that is operated by one laborer and it can also be used for lite injection and vacuum injection. The hand pistol dispenses resin from a storage unit as small as 30 L.

The mold consists of one bottom part (including the bottom cavity, floor support and lock clips) and one top part (top cavity and cylindrical rod handles). The top and the bottom parts were made from composite material (polyester matrix reinforced with glass fibers) and from surface finish made from aluminum material with rubber inserts to avoid resin leakage.

Raw Materials

Fiber reinforcement: 0.80 kg (23% volume fraction). Resin: 0.82 kg (55.59% volume fraction). Filler: 0.69 kg Calcium carbonate $CaCO_3$ at (19% volume fraction) for each E-glass hood part. The remainder 0.13 kg (2.41% volume fraction) includes the catalyst and accelerator together. Refer on Table 3 for all material's features and specifications.

Table 3. Materials features and specifications.

		Resin		
Component Name	Reichhold Polylite	Biopoli BP 507		
Density	1100	1100		kg/m^3
Viscosity	0.12	0.25		Pa·sec
Price	8.32	8.32		MU/kg
Polymer System	Polyester	Bio-Polyester		
Reaction Rate Coefficient k	1.61×10^8	1.61×10^8		sec
Activation Energy	75,100	1.61×10^8		J/mol
		Reinforcement		
Component Name	Bi-axial woven Glass	Bi-axial woven Ramie	Bi-axial woven Jute	
Fiber Density	2600	1500	1550	kg/m^3
Fiber Diameter	5.4×10^{-5}	3.4×10^{-5}	4.0×10^{-5}	m
Price	8.32	35	14.8	MU/kg
		Catalyst		
Component Name	Brasnox			
Density	1100	kg/m^3		
Price	9.2	MU/lt		

Part Weight and Thickness

The polyester glass fiber reinforced hood produced weighs 2.44 kg. Its characteristics are presented in Table 3. The hood is shaped to a constant thickness of about 4 mm in a closed mold. The volume fraction (Vf%) is assumed to be constant for the PBCM but in practice it may vary due to variable fiber (apparent) diameters and natural fiber swelling during processing.

The materials identified in the Resin Transfer Molding Solution represent the following percentages regarding volume fraction (Vf%) of the hood illustrated in the pie chart of Figure 3.

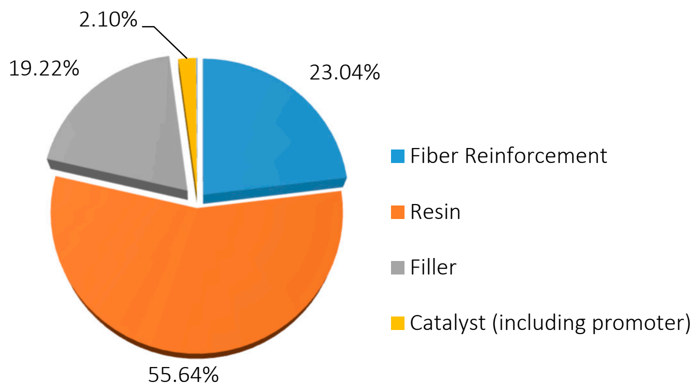


Figure 3. Volume fraction of material composition.

The maintenance will cost 10% of the initial machinery price (auxiliary over lifetime). The auxiliary equipment, installation, and overhead costs are all estimated to approximate a series of complicated costs encountered in the machine setup and day to day operation and upkeep.

Productive time is a percentage of the available work hours that are actually used for part production. Tool change over time is incorporated into this estimate.

Cycle time, one of the most critical values of the process, determines the maximum part production rate and thus the number of parts the capital cost can be spread over.

3.1.3. RTM Molding Cycle Times

Many of the process steps of the RTM can be completed outside the production site, before or during the injection takes place. As an example, the fabrics cutting and storing into kind of layered preforms can be run in other areas of the workshop. Also, the preparation of the mold can take place in another spot of the production line away for the RTM injector.

During preparation of the mold, three different liquids are applied to the mold's cavity so as to ensure appropriate part removal. At first, resin thinner is applied to take off small drops or cured resin concentrations from the mold's surface. Then we applied a sealing liquid to provide a base coat and increase the mold release effectiveness. This is applied three times in total. Finally, four layers of the liquid demolding agent are passed on the mold surfaces to facilitate the composite release from the mold's cavity. A breakdown of these steps and the times required is shown in Table 4.

Soon after, and when the part is cured (around 10 min after injection), the finished part can be extracted. With the use of hand tools if necessary, or with an air pistol, the laborer will carefully remove the finished part from the mold. In the last step, the part should be inspected and tested for its suitability to be assembled to the car chassis. At this point, the part is measured by an ultrasonic machine for its thickness and, occasionally, trimming will be required so that the excess material is removed. In that case, the parts are complementarily forwarded to the painting/trimming shop to be additionally processed.

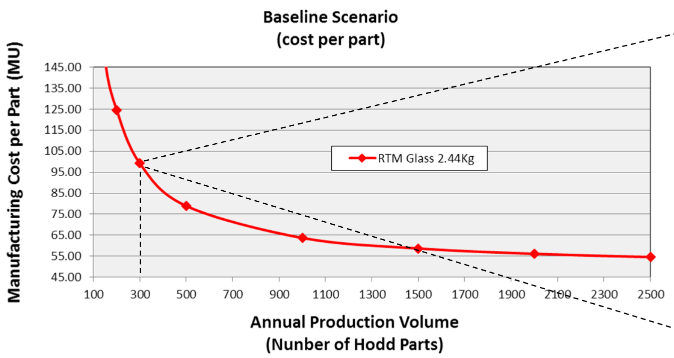
As witnessed on site, Ancel's plant is equipped only with one RTM injector machine and since production runs for the hood are small; there is no need for purchasing additional injectors to increase performance. Hereafter, one mold station is considered to be efficient, and no scenarios will be studied regarding parallel stream RTM production. Under a two-shift operation per day, 16 parts can be produced and all hoods are cured at room temperature, and stacked before the next phase.

Table 4. RTM process steps.

Tasks Done Inside Mold Area		Time (seconds)
680 s	Open Mold	80
	Demold Part	65
	Apply Thinner	55
	Apply Sealer	165
	Apply Demolder	220
	Place Fabric in Mold	15
	Close Mold	80
Tasks Done Next to the Mold Area		**Time (seconds)**
2866 s	Preparation of Resin (50 L)	282 (for 20 parts)
	Cut Fabric	223
	Place Mold Next to the Injection Gun	65
	Injection	40
	Block Exit Points	15
	Resin Gel	600
	Post Curing Part	1600
	Inspection/Trimming	80

3.1.4. Model Assessment Summary for Baseline Scenario

Under Ancel's baseline manufacturing conditions and considering an annual production volume of 300 parts per year, the hood was estimated to have MU 100 of production cost. This includes MU 2.0 for tooling, MU 35.6 for material, and MU 12.5 for the main machine (RTM injector) cost. Manufacturing costs for production volumes from 100 to 2500 parts and a complete cost breakdown of 300 parts is shown in Figure 4.



Variable Cost		
Material	MU 35.6	35.6%
Labor	MU 19.2	19.2%
Energy	MU 7.6	7.6%
Fixed Cost		
Main Machine	MU 12.5	12.5%
Tooling	MU 2.0	2.0%
Building	MU 8.3	8.3%
Auxiliary equipment	MU 1.9	1.9%
Maintenance	MU 2.4	2.4%
Total	**MU 100.0**	**100%**
Tool Investment	**MU 40,103.78**	

Figure 4. Baseline cost of polyester/e-glass.

3.1.5. Natural Fibers Incorporation (Ramie and Jute)

Recently, attention has been given to the abundant jute [50,51] and the stiff ramie [52–54]. Ramie and jute fiber mats are considered as alternatives to the glass fiber baseline scenario. Those two alternatives have been proven to be acceptable candidates with adequate tensile and flexural performance to be used as replacements in the buggy hood. In addition, they have the potential to cut down the environmental effect of the synthetic materials that derive from petroleum resources. Table 5 lists the characteristics of the alternative scenarios fibers along with the baseline e-glass. All information about fiber prices was acquired from the Ancel sales department. The ramie-reinforced hood used here is from a past study of Koronis [43], the jute-reinforced hood was proposed by another familiar study of Alves [42]. Those hoods have mechanical performance approximate but are not equivalent to the glass reinforced hood. One of the main reasons for this variation is the different fabric weights (a.k.a grammage) and Vf% of each option. However, all composites were manufactured by six bi-axial layered fabrics across all scenarios. Refer to Table 5 for reinforcement related characteristics and cost.

Table 5. Reinforcement related characteristics.

Reinforcement	Vf% in Hood	Layers	Grammage (g/m^2)	Density (kg/m^2)	Price (MU/kg) *
E-glass	21	6	300	2600	8.32
Jute	31	6	310	1550	14.8
Ramie	20	6	190	1500	35

* Including shipment cost.

As seen in Figure 5, which depicts the hood baseline against the green alternatives, both E-glass and alternative scenarios have high cost at a low volume production for the targeted production volume. However, jute is the least expensive solution at all production volumes in either scenario. Table 6 shows a comparison of all three choices of fiber reinforcement in different batch sizes. As indicated in this table, ramie fiber integration in the green composite does not represent a competitive candidate in terms of economic performance. It cannot take advantage of the glass-reinforced baseline scenario in the same manner that jute fabrics would, and therefore process optimization will be considered in order to assess whether a further cost cut for ramie is possible.

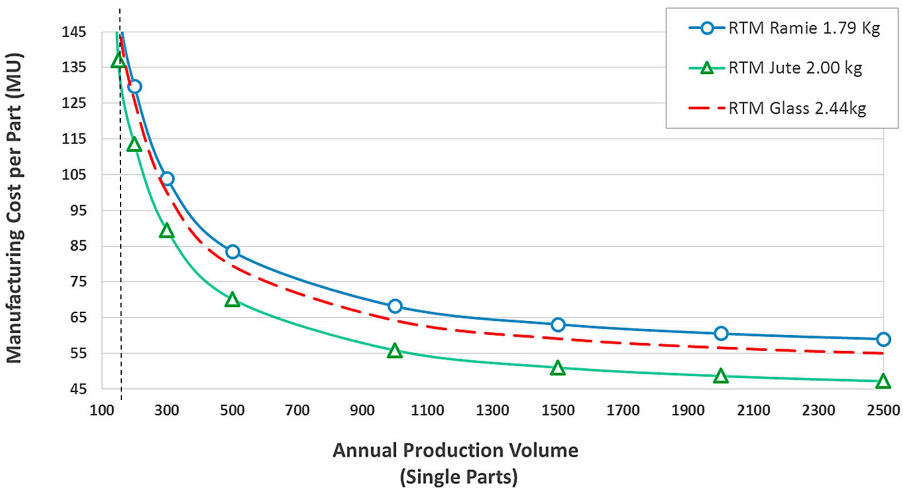


Figure 5. Hood baseline scenario against alternatives.

The point is that the price of the man-made ramie fabric is very high, including increased shipment cost (from China), compared to the glass-fiber fabrics which are produced by a supplier based in the same industrial zone where Ancel runs its facilities. The biaxial woven ramie fabrics were more expensive than E-glass at almost 4 times the price (at MU 35/kg). These factors are adversely affecting the production cost for each ramie-reinforced hood which for this case is 4% higher than the conventional glass-reinforced solution at 300 parts. These cost penalties are roughly the same for the range of annual production volumes analyzed. Jute fabrics have in fact lower price when compared to ramie as well because jute is a native crop of Brazil and in a high worldwide annual harvesting yield. Even if jute was more expensive than per unit weight glass, the jute composite is 18% lighter than the glass and therefore it takes the cost benefit over the glass baseline.

Table 6. All costs per part for baseline and alternative scenarios.

Plot (Parts)	Glass (MU)	Ramie (MU)	Jute (MU)
50	355.3	359.4	329.1
150	150.8	154.8	137.1
200	125.7	129.8	113.6
300	100.0	104.0	89.4
500	79.6	83.6	70.2
1000	64.2	68.2	55.9
1500	59.2	63.2	51.1
2000	56.6	60.6	48.7
2500	55.1	59.1	47.3

Typically, with the incorporation of the natural fiber fabrics in a composite as opposed to glass fabrics, there are weight savings attached. Ramie composites are lightest among the three candidates. Actually, both ramie and jute are less dense than the glass fiber and, consequently, the green composites are also lighter (see Figure 6). The ramie composites hood is the lightest among the three candidates (at 1.78 kg) followed by jute (at 2.0 kg) and glass (at 2.44 kg). This attribute is explained because the ramie hood requires less fiber volume fraction to reach an equivalent structural performance to the reinforced by the glass, as studied by Koronis [43].

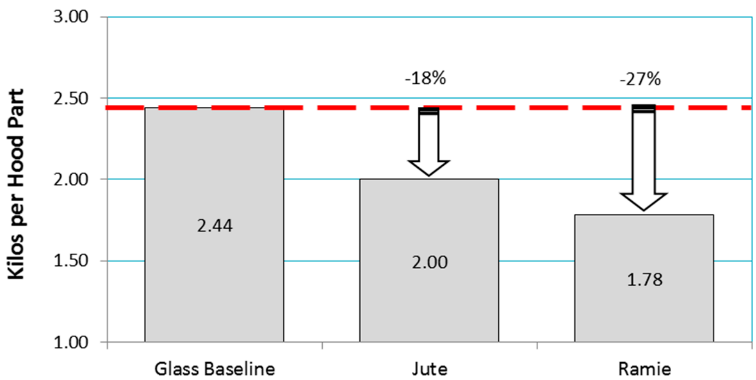


Figure 6. Summary of weight reduction potential.

3.1.6. Optimization Using Constituent Materials and Tool Upgrade

Two methods for improving the RTM baseline manufacturing approach were considered for performance enhancement and cost reduction: upgrading the injector machine (actually converting it to Lite RTM (LRTM) and optimizing the labor use). At first, a vacuum pump will be installed to the injector in order to convert it to LRTM. By this improvement, labor use will be supplementary optimized in terms of performance. The reason for this is that the upgraded technique requires less labor as only one worker is needed to run this manufacturing process.

Unlike for the conventional RTM, two dedicated workers were used for the one-part production hood, one handling the injection gun and another non-dedicated to seal the mold. At first there is one laborer controlling the injection's gun nozzle releases the flow valve and injects resin into closed molds. A second laborer is needed to block the injection and release point when the other laborer puts the pistol away and place it in back to the injectors' base for the next injection. The above process in unnecessary for LRTM as one laborer can handle the whole process in a different setting. The process, therefore, becomes slower due to its moderate pressure (vacuum assisted). However, more precision is attained regarding surface finish since less manual post mold rework is required. This is possible because of the vacuum which eliminates voids on the molded part surface. That subsequently leads to fewer rejects and scrap material which agree with the results of Hutchinson, Schubel and Warrior [55]. In addition to that, with the LRTM upgrade, the workspace will be considerably cleaner than traditional RTM, as also suggested by Harper [56].

When considering the optimized LRTM conditions compared to the baseline, a more economical production may be found and the process may become more competitive compared to the glass baseline. The first set of alternative approaches is addressed with ramie and the second one is for jute fabrics. The changes over the baseline (of Table 1) are described in Table 7 within brackets, where we summarize the manufacturing-specific issues of the PBCM for the alternative LRTM scenario. All contents are described previously in Section 0; however, in this setting we include updated equipment, labor content and fewer rejects. Furthermore, additional investment cost is envisioned for upgrading the injector and its supporting equipment.

Table 7. Main PBCM elements considered for Lite RTM (LRTM).

• Consumables ○ **Raw materials** ○ **Process materials** ○ **Recycling** • Equipment utilization (*updated) ○ **% of the line required** • Building space • Energy	• Effective production volume (**Fewer rejects are considered**) ○ **Labor (*updated)** ○ **Indirect** ○ **Direct** • Equipment requirements ○ **Press, tooling** • Capital (*updated) ○ **Extra cost**

The cost savings of all alternative strategies to manufacturing are plotted in Figure 7, where all possible cost reduction is illustrated. The arrows indicate the cumulative cost reduction potential relative to the baseline.

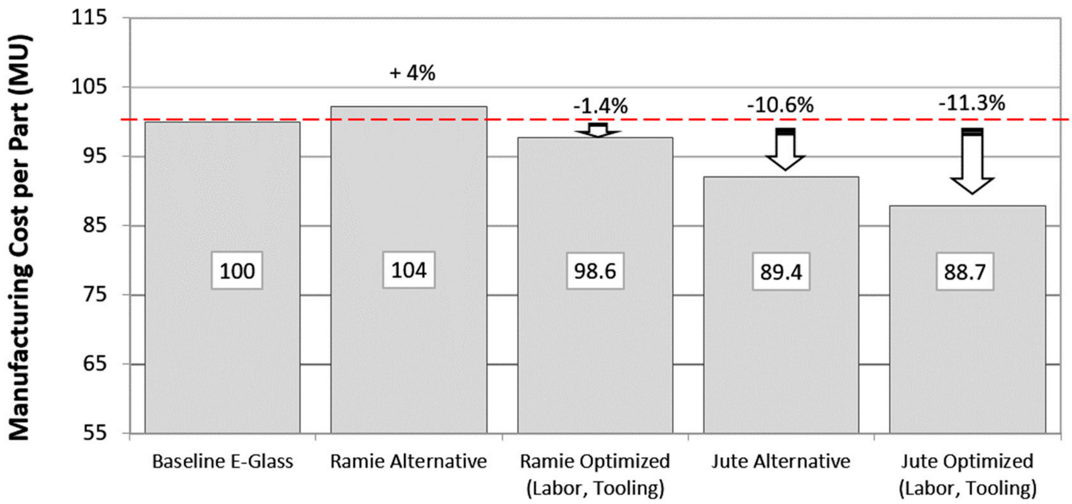


Figure 7. Cumulative cost reduction potential from optimized approaches at 300 parts/year.

An optimized Ramie production line can reduce cost by 5.4% when compared to the non-optimized Ramie scenario. In the non-optimized ramie scenario, there was no improvement observed in the total cost per part. Contrarily, an additional increment of 4% was attributed to the higher prices of ramie fabrics. Still, the optimized ramie alternative strategy does not reduce the manufacturing cost per hood part significantly. Although using the cheaper jute fabrics, the cost can be reduced by an order of 10.6%, followed by an additional drop by 0.7% in cost when labor and tooling optimization are considered. As such, the optimized jute scenario appears to be the lowest cost scenario among all.

The outputs of the cost model of Figure 7 are listed in Table 8 by cost category. Furthermore, one can deduce from these numbers that the largest accumulated percentage of the total cost is around the material cost, which is the most dominant category. In the optimized scenarios, material cost is lower compared to the optimized counterparts which are a result of the efficient use of material due to upgraded machinery and reduced rejects generation.

Table 8. Cost breakdown per hood part for all scenarios.

Cost Category (MU)	Glass Baseline	Jute Alternative	Jute Optimized	Ramie Alternative	Ramie Optimized
Material Cost	36.2	25.7	24.9	36.1	35.1
Labor Cost	19.2	19.5	9.3	19.5	9.3
Energy Cost	7.8	7.8	7.8	7.8	7.7
Main Machine Cost	12.5	12.5	16.4	12.5	16.4
Tooling Cost	2.0	2.0	2.0	2.0	2.0
Fixed Overhead Cost	9.5	10.6	12.4	10.5	12.4
Building Cost	8.4	11.1	11.0	11.1	11.0
Auxiliary Equipment Cost	1.9	1.9	2.5	1.9	2.5
Maintenance Cost	2.5	2.7	3.0	2.7	3.0
Total Cost	100	89.4	88.7	104	99.4

3.2. Environmental Performance Assessment

The environmental performance of the composite was quantified using the database and tool (Eco-Audit) available from CES Selector© from Granta Design Ltd. [35], to identify traits and areas that need improvement regarding its overall manufacturing/energy footprint. Through that assessment, the several forthcoming scenarios are compared with each other in an attempt to draw out meaningful conclusions as regards their environmental footprint.

3.2.1. Baseline Scenario: The Glass Reinforced Hood

The reference baseline hood part is produced under the conditions described in Section 3.1.1 at 300 batch size. The hood is molded and fixed on the buggy's chassis; then the buggies are to be transported to Sao Paolo Brazil over a distance of 200 km by a 32-ton truck where ideally the buggy's distribution center will be. Table 9 shows the data as introduced in the Eco Audit Tool spreadsheets for the three different phases. Two well understood environmental indicators—Energy Usage and CO_2 Emissions—come out of this analysis. The Energy Usage throughout the product Life Cycle, which can be converted to CO_2 emissions during the product's life [35,57].

Table 9. Eco-Audit tool inputs.

Step 1: Material and manufacturing, joining and finishing				
Component name	Material	Process	Recycled	Mass (kg)
Car hood, 318 units	Polyester	Polymer Molding	Virgin (0%)	1.5
Mat Fabric, 318 units	Glass, E-Grade	Fabric Production	Virgin (0%)	0.8
Treatment Name	Material	Process	Secondary	Area (m^2)
Surface Finishing, 300 units	Polyurethane Aliphatic	Painting	Cutting/Trimming	102
Step 2: Transport				
Stage Name	Transport Type		Distance (km)	
Finished part to the point of sale	32 tons track		200	
Stage Name	Transport Type		Distance (km)	
Raw materials transfer	14 tons track		637	
Step 3: Use phase: mobile mode [i]				
Fuel & Mobility Type	Usage (days/year)	Distance (km/day)	Product Life (years)	
Gasoline-Family Car	80	40	5	

[i] The mobile use mode is defined by three parameters: the transport type, efficiency, and the distance traveled over the product's life.

3.2.2. Materials, Manufacture, End of Life

At the first stage, the Eco Audit Tool assesses the component's inputs that are involved with the part's manufacturing. In that step, we introduced the energies and CO_2 profiles for the materials and processes to the project database. Energy recovery was assumed in the percentages shown in Table 10 where the disposal phase inputs for glass, the reference composite scenario are listed. In the study of Alves et al., 2011, mechanical recycling of the composite materials was performed successfully although at low percentages (11–12%) due to low recycling efficiency of bi-axial reinforced composites succeeded. As such, the remainder percentage granulated fractions and sieving will end up in landfills at the disposal scenarios of the composite materials. The remaining material was assigned to incineration and landfill scenarios based on Brazilian government reports. It is pointed out that 0.2% of the total Brazilian waste is incinerated, 59.5% is collected but not treated and 20% is neither collected nor controlled. This data shall be adopted for use in our evaluation to define the End of Life potential (EoL), as long as the same types of hoods were subjected to investigation under an identical manufacturing process of the very same workshop of Ancel.

Table 10. Disposal phase (energy inputs, outputs) for reference composite.

Component	Eol Potential	% Recovered
Matrix	Re-manufacture	11.0
Reinforcement	Landfill	20.0
Total		

3.2.3. Transportation

This section relates to the transport of the finished product from the source of manufacture to the customer. Basically, we introduce the energy and CO_2 profile of the selected transportation mode from a look-up table that reveals the energy requirements and carbon emissions, identifying the phases of life that create the highest burden. This energy usage and CO_2 footprint values are combined with the product mass and distance to determine the environmental impact of each stage. Table 11 lists the transportation profile as regards the materials used for the automotive hood composition and its transportation to the point of sale after the installation onto the buggy body. All the intervals mentioned refer to the distance between manufacturer and formulators while the car sales refer to the distance between Ancel and local distribution depot. All information about allocation was acquired from Ancel database.

Table 11. Breakdown of raw materials and phases by transport stage.

Stage Name	Transport Type	Distance (km)
Finished car to the point of sale (Sao Paolo)	32-ton truck	200
Raw materials resin	14-ton truck	240
Fiber	Light goods vehicle	20
Catalyst	Light goods vehicle	130
Demolder	Light goods vehicle	67
Total		657

3.2.4. Use-Energy and Carbon Footprint

At this stage of analysis, the software retrieves an efficiency factor for the chosen energy conversion mode. This can be found in a look-up table, and the choice is in Table 12. Fuel consumption and CO_2 emission of products generally increase with their weights. In order to calculate the environmental impact, the following assumptions have been taken into consideration.

Table 12. User phase inputs for car usage.

Mobility Type	Usage (days/year)	Distance (km/day)	Product Life (years)
Gasoline-Car	80	40	20

Source: Serra and Credidio [58] and Ancel sales department.

More specifically, on the baseline scenario, the product life of the car is taken to be 20-years, as commonly occurs for most Brazilian automobiles. This expected use-phase life is based on the Brazilian National Association of Brazilian Auto Parts Manufacturers (Sindipeças) Reports [58], which contain valuable data about the auto-parts sector in Brazil. Since the hood is a component of a mean of transport, it shall be related to the mobile mode on the transportation systems. It is assumed additionally that the buggy car will be used at least once per week and will be used for a 40-km route in a hypothetical round trip to the beaches of Rio de Janeiro City-Brazil, in the state of Rio de Janeiro. Since the use phase values will be equivalent for all scenarios considered, it is not of vital importance to have authoritative values for distance and days of use to run the comparison. As such, these values are considered valid for their pertinence of use.

3.2.5. Environmental Assessment Summary for Baseline Scenario

The energy and CO_2 footprint of each phase of life of product are plotted in the form of a detailed breakdown (material, manufacture, transport, use, and end of life) depicted in the chart in Figure 8. Table 13 shows the energy and carbon footprints of the materials and manufacturing processes. The EoL represents the end of life savings realized in future life cycles when utilizing the recovered material or components. The bars for the energy and carbon contributions to the first life as bars of solid colors, and show the potential energy and carbon saving (or penalty) as a separate, cross-hatched bar.

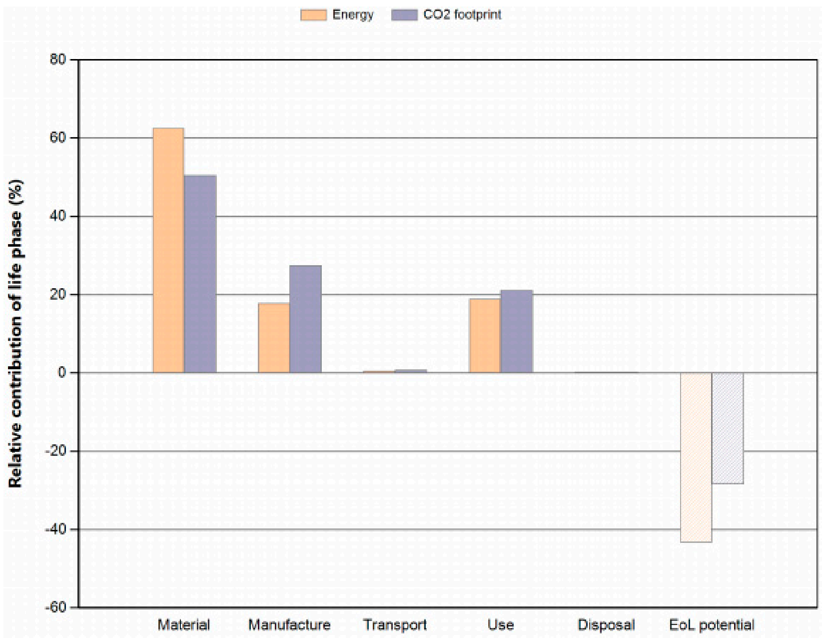


Figure 8. Eco-Audit summary chart for breakdown energy associated with each life-phase for E-glass reinforced polymer hood.

The information above enables a comparison of the impact that each phase of life has in the entire life cycle, how one can decrease this impact, and what implications can potentially have in the other phases of life. It is deduced that the most energy-intensive phases and overwhelmingly dominant environmental stressors (Energy and CO_2 Footprint), is the Material Phase (62.6%, 50.4%)

followed by the Manufacture Phase (17.7%, 27.4%), and Use Phase (18.9%, 21.2%). It is, however, clearly distinguished that the greatest consumed energy is, in the first phase, spent on the materials. Here, one phase of life consumes far more energy than all the others put together. Subsequently, it makes sense to focus first on this most dominant life phase, where the potentials of choosing alternative material that reduce energy and carbon are higher.

Table 13. Eco-Audit report of the energy and CO_2 footprint for all hood scenarios.

	Glass Part		Ramie Part		Jute Part	
Phase	**Energy (MJ)**	**CO_2 Footprint (kg)**	**Energy (MJ)**	**CO_2 Footprint (kg)**	**Energy (MJ)**	**CO_2 Footprint (kg)**
Material	47,383	1977	30,004	1091	41,389	1578
Manufacture	13,417	1073	10,122	810	10,077	806
Transport	441	31	90,250	6048	2032	144
Use	7713	548	6152	437	6836	485
Disposal	147	10	146	10	157	11
Re-manufacture matrix	96	7	74	5	72	5
Landfill fabric	51	3	25	2	40	3
Downcycle resin	-	-	47	3	45	3
Total (for first life)	69,101	3639	136,673	8395	60,491	3025
(EoL) potential	−3278	−111	−2828	−99	−2754	−97

The material use particularly stands out because E-glass fibers as well as polyester (the constituents of the reinforcement) are synthesized from raw materials of high embodied energy. The use phase appears to be among the most dominant stages because of the gasoline engine intended for the buggy where the hood will be assembled. It is assumed that if an electric engine was used instead to power the buggy, the use phase would have been less impactful when compared to the other stages considering the low-carbon electricity sources of electric vehicles (EVs) for the scope of this study. That is something that Ancel could consider in the future given the current transition to more energy efficient means of transportation. Indeed, that would reduce by an order of 10% the Use Phase and by 15% the CO_2 emissions.

As for the EoL potential, there are some potential benefits when recycling the hood materials at the end life of buggy. The hood is partially downcycled as mentioned in Section 3.2.2, which leads to materials with lower durability performance and lower embodied energy. In general, the energy level required for downcycling material by comminution is similar to that for producing the virgin aggregate or filler. As a result, for the whole batch; a total energy of 3278 MJ can be recovered at the end life of the material, which represents 6.9% of the total energy. Accordingly, a net reduction of CO_2 emissions by 112 kg (counting for 3.1% of the total CO_2 emission) can be obtained by downcycling.

3.2.6. Natural Fiber Incorporation and Optimization

In these scenarios for green composite (ramie and jute hood), the fibers were used along with a mix of polyester and natural renewable resources. As described in Section 3.1.5, the optimized LRTM can provide less scrap material and ideally a better surface finish, which contributes to saving materials and thus energy. The green resin considered in that scenario is based on the composition of BioPoli 507 resin [59] with the incorporation of reused materials. Accordingly, 20% of the matrix material is renewable, which contributes to a degree of impact on the material and disposal phase. Therefore, energy recovery was assumed in the percentages as shown in Table 13, together with the EoL potential for each constituent.

Several observations can be drawn out of this assessment as regards energy spent and the CO_2 emissions generated per mass (Figure 9). At first sight and as determined by the column charts, ramie composites demonstrated to be less energy and carbon intensive in all phases under comparison except from the Transportation Phase. This is explicable to some extent because ramie reinforced composites will predominantly be lighter and thus will have less total product mass than the ones made of glass fiber. Figure 9 shows the benefits of green composites use regarding the materials, manufacture and use phase. This is a result of the smaller amount of embodied energy associated with the primary material production of natural ramie fibers. However, in terms of transportation, the ramie scenario is ranked worst, which is attributed to the long distance that the fibers need to travel until reaching the manufacturing facility. Jute is more favorable (being a local Brazilian fabric) and glass is the optimum, as it is fabricated next door (facilities inside the industrial area where Ancel is located).

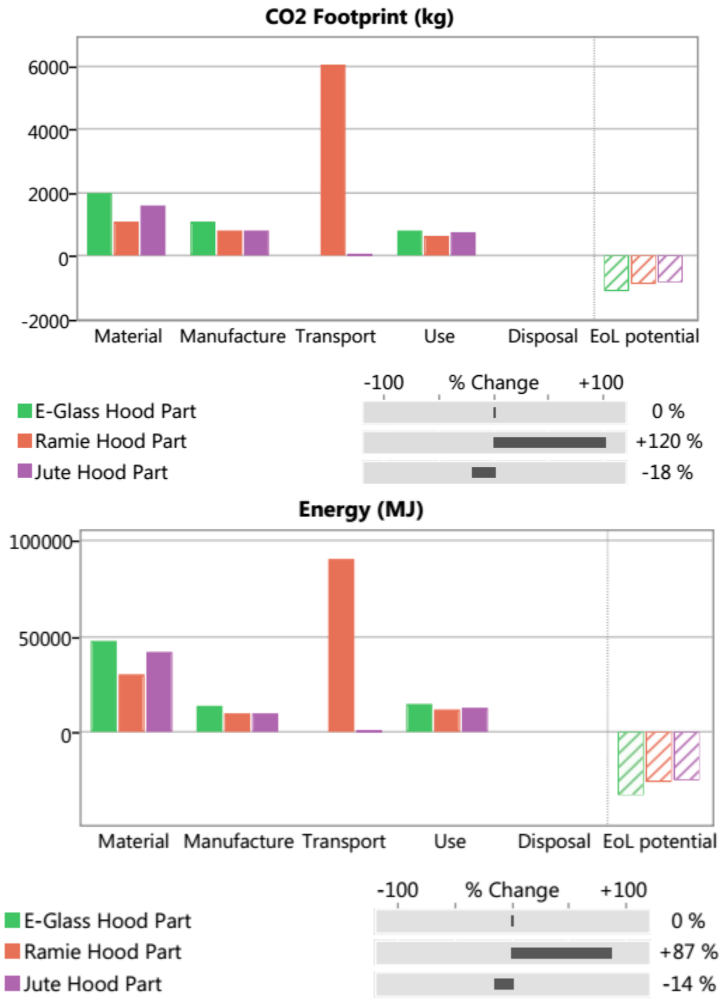


Figure 9. Glass fiber hood against ramie and jute eco-audit summary charts.

As determined by the report charts of Eco-Audit, 36% less energy and 44% CO_2 per kilo will be generated when swapping from glass to ramie fabrics reinforced composites in terms of material use. The value for the EoL potential is not very high as composite materials and especially thermoset materials are very unlikely to be recycled after the use but partially down-cycled for their utilization in byproducts and/or fillings in other composites. Among all three scenarios, jute seems to be a good candidate for all cases, ranking the best score in overall performance, which is already 14% in terms of energy and 18.5% less CO_2 footprint over the glass fiber composite baseline. The analytic values of Eco Audit reports for all scenarios are presented in Table 13.

4. Discussion

The main goal of this study was to assess the financial and environmental costs of a hood part during its design phase.

To meet the financial goal, we adopted the PBCM as an instrument for engineering and management analysis. The outcome showed that not all alternative scenarios are cost efficient compared to the baseline. Consequently, three methods for improving the RTM baseline manufacturing approach were considered for performance enhancement and lowering cost: upgrading the injector machine runs (by converting it to LRTM), optimizing the labor content and optimizing the raw materials utilization. The examples presented here demonstrate that there are real opportunities for this approach for product and process design, which can lead to more cost-effective designs. According to this, it is possible to reduce the production cost (by substituting jute fibers for glass fibers and optimizing the RTM process) by up to 10.1%. Although a larger and more expensive tool is needed for the new machine setting, the net result is a significant cost saving. Normally, most of the car makers would have been resistant to deploying low volume productions as the market is insufficiently large to pay for tooling and start-up technology around which their manufacturing system is based. However, the expenses for an RTM upgrade seems to be cost-efficient in the manufacturing process for this small-scale production. Additional cost reduction can be realized if the batch is increased significantly (e.g., at 5000 parts) as a result of increased market demand for additional parts.

Regarding the environmental profile of the scenarios under discussion, the advantages of swapping from synthetic fiber to natural fiber are clearly shown by the Eco-Audit Tool analysis. Throughout the life cycle of a product, we identified the most relevant critical phases of a system for a set of environmental impact indicators (MJ per part and CO_2 equivalent per part). Energy saving and CO_2 decrease are among the benefits for all phases that are under comparison. Greater savings are envisaged at the stage of material usage and product use where the type of materials employed and the weight of the final part show a positive contribution to the environmental impact. Similar observations were reported by Alves et al. (2011) as regards the natural fiber incorporation into the composite.

5. Conclusions

Green composites require improvements to best compete with traditional composites, especially when the per-item cost is the key driver. The trend can be reversed in the sense that the necessity for environmentally conscious solutions can overturn the value chain and put a premium price on the environmental impact of current solutions. An essential point is whether these green composites can be engineered to reach the ecological and mechanical performance of their predecessors while having the lowest possible cost.

The use of materials of greener profile with embodied energy associated with their production can significantly contribute to reducing the environmental impacts. Moreover, as showed herein, the addition of plant-based content and natural fibers acts absolutely as a complementary effect and increases its environmental performance given that both are deriving from annually renewable resources. This impact can be further mitigated by exploiting local resourced constituents. The location of the natural fibers plantation was revealed to be of extreme importance and the sole main factor for discarding ramie as the most environmentally friendly fiber in this study. It is therefore not enough to undertake materials substitution without taking into account the material's origin in order to maximize the environmental benefits.

These aspects combine to suggest that the potential adoption of natural fibers in composite structures is indeed promising, although it calls for specific attention to a few key elements. Forthcoming studies are recommended henceforth to explore ways in which these green composites can be further optimized for recycling and downcycling purposes. Ultimately, additional assessment studies will have to accumulate knowledge on this field to potentially indicate that plant-based reinforced composites are environmental and economical alternatives to traditional synthetic composites.

Acknowledgments: The first author gratefully acknowledges the MIT Materials System Laboratory researchers, Jeremy Gregory and retired MIT senior researcher Daniel Whitney for providing all assistance needed during his visit at the Massachusetts Institute of Technology. Moreover and foremost, he wants to thank the owner, the supervisor of his internship and also the helpful personnel of Ancel Ltda in Rio Claro—Brazil, for receiving him and providing him with all appropriate data required for completing this work.

Author Contributions: Arlindo Silva conceived and guided the material selection phase of the afffiliated project and contributed to environmental assesment. Georgios Koronis analyzed the experimental data and interpretation

of the cost data. The latter has drafted the outcome of this work and the first made a critical review and a substantial revision of the present manuscript overall.

Conflicts of Interest: The authors declare no conflict of interest.

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